CAMBRIDGE UNIVERSITY PRESS
C. F. CLAY, MANAGER
London: FETTER LANE, E.C.
Edinburgh: 100 PRINCES STREET

New York: G. P. PUTNAM'S SONS
Bombay and Calcutta: MACMILLAN AND CO., LTD.
Toronto: J. M. DENT AND SONS, LTD.
Tokyo: THE MARUZEN-KABUSHIKI-KAISHA

ELECTRICAL ENGINEERING

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VOL. I

INTRODUCTORY

Cambridge:
at the University Press
1915

Cambridge:
PRINTED BY JOHN CLAY, M.A.
AT THE UNIVERSITY PRESS

PREFACE

THIS volume is designed to serve as a text-book for Elementary Courses in Electrical Engineering in technical institutions. Naturally one of the main purposes of such a book is to teach first principles and while matters of practical utility have been included, an endeavour has been made to avoid overloading it with descriptive details which are more appropriate to oral than to written exposition.

In view of the increasing use which is being made of potentiometer methods, a somewhat fuller treatment of the potentiometer is given than is usual in elementary text-books. The author has found the use of the potentiometer at an early stage a valuable means of correcting the tendency of students to be content with rough experimental results; this tendency is only natural as much of the apparatus used by students in their earlier courses is of simple design in order that the principles involved may not be obscured by elaborate manipulative details.

The author wishes to express his indebtedness to the following firms for permission to use their illustrations and for the loan of blocks: Messrs Evershed and Vignoles for Figs. 22, 23, 70, 71, 72, 73; Kelvin, Bottomley and Baird for Figs. 17, 18, 36, 39; Nalder Bros. and Thompson for Figs. 15, 16, 19, 20, 21, 25, 28, 76, 77, 118, 119; W. G. Pye and Co. for Figs. 10, 29, 41, 42, 61, 63, 78, 89, 90, 94, 96, 97, 109; R. W. Paul for Figs. 24, 26, 27, 30, 31, 32, 33, 35, 37, 38, 40, 64, 67, 68, 74, 75, 95, 100, 103; H. Tinsley and Co. for Figs. 65, 66, 69, 91, 93, 99; the D. P. Battery Company for Figs. 112, 113; the Edison Accumulator Company for Figs. 121, 122, 123, 124, 125, 126, 127, 128, 129; the Electrical Power Storage Company for Figs. 114, 115, 116, 117; and to Messrs Gambrell Bros. and the Sunderland Forge and Engineering Company for the originals of the illustrations of their manufactures (Fig. 88 and Figs. 48, 49).

T. C. B.

20 *January* 1915.

CONTENTS

CHAPTER I

HISTORICAL INTRODUCTION

CHAPTER II

CURRENTS OF ELECTRICITY

CHAPTER III

MAGNETISM

CHAPTER IV

CURRENT MEASUREMENT

CHAPTER V

ELECTROMOTIVE FORCE

CHAPTER VI

MEASUREMENT OF RESISTANCE

CHAPTER VII

THE POTENTIOMETER

CHAPTER VIII

BATTERIES

CHAPTER IX

ELECTRIC LIGHT

CHAPTER I

HISTORICAL INTRODUCTION

The first recorded observation of what we would now call an electrical phenomenon, was that amber when rubbed attracted light bodies. This property is said to have been described by Thales of Miletus, about 600 B.C., but the science of electricity dates from the investigations of Dr Gilbert of Colchester (1540-1603) who found that a large number of other substances possessed the same property and that the attraction was not confined to *light* bodies. He accounted for these phenomena by supposing that the rubbing caused the substance to possess something which he called "electricity." The substance is then said to be "electrified." The word electricity is derived from the Greek word for amber, *electron*.

It was soon found that electrified bodies either attracted or repelled each other and the discovery of electric repulsions led to the view that there are two kinds of electricity. These were originally called vitreous electricity and resinous electricity, but they are now always referred to as positive electricity and negative electricity*. Fresh experiments from time to time brought new contributions to the theory of electricity of which the fundamental propositions are: that there are two kinds of electricity (called positive electricity and negative electricity); that ordinary or "non-electrified" bodies possess equal and (apparently) unlimited amounts of both kinds; that there is repulsion between all parts of electricity of a like kind, attraction between unlike kinds; and

* It is quite feasible to maintain that there is really only one kind of electricity —say, the positive, and regard a body alleged to possess negative electricity as simply having less positive electricity than it has when non-electrified. Both views amount to the same thing in practice and only differ in verbal expression.

that the forces of attraction and repulsion are greater the less the distance between.

The explanation of the attraction of amber—when rubbed and therefore electrified—for a non-electrified body may be taken as a typical example of the application of the theory. Electricity (negative, in this case) is produced on the amber by the rubbing, and this attracts the positive electricity on the other body and repels the negative, thus separating them, as indicated in Fig. 1 by the signs + and −. *A* represents the amber, and *B* the other body. The attraction of the negative electricity on the amber *A* for the positive electricity on the body *B* exceeds, on account of its closer proximity, its repulsion for the negative on *B*, and therefore *A* attracts *B* on the whole.

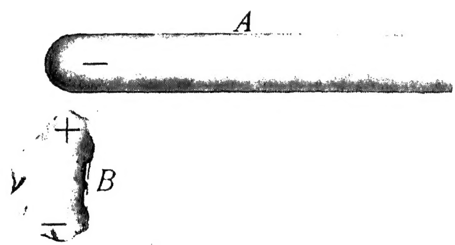


Fig. 1.

It was very early noticed that certain substances, such as metals, behaved differently in some respects from the majority of other substances. Suitable experiments soon proved that this was due to their power of allowing the electricity to pass freely through them, or of "conducting" electricity, as it was called. From this point of view, substances were classified into conductors and non-conductors. Non-conductors are sometimes also called dielectrics or insulators.

Dr Benjamin Franklin of Philadelphia (1706–1790), who was fortunate enough to bring down electricity from thunder-clouds without mishap, was the first to prove experimentally that lightning is produced by electricity. He also devised the lightning conductor for the protection of buildings.

Charles Augustin de Coulomb (1736–1806), by means of his Torsion Balance, proved that the force between two quantities

of electricity varies inversely as the square of the distance between them*. This discovery enabled a system of absolute measurement of quantities of electricity to be established.

The name of Luigi Galvani (1737–1798), Professor of Anatomy at Bologna, is associated with several electrical matters owing to his discoveries in animal electricity. To this day, medical men often use the term " galvanism " in a sense which is indistinguishable from electricity itself.

An entirely new class of electrical phenomena was opened up by the discoveries of Alessandro Volta (1745–1827), Professor of Natural Philosophy at Pavia. Volta discovered the production of electricity by a suitable arrangement of metals in contact (voltaic pile) and devised the production of currents of electricity from cells containing appropriate chemicals (voltaic cell). The international unit of electromotive force is named the volt in honour of Volta, whose original papers fill five volumes and whose work supplied many of his contemporaries with clues for their researches.

The first discovery connecting electricity with magnetism was made by Professor H. C. Oersted of Copenhagen in 1820. He found that a current of electricity could be made to deflect a compass needle and therefore produced magnetic force. Soon after, André Marie Ampère (1775–1836) found the precise relation between the magnetic force and the arrangement of the conductor carrying the current of electricity producing it, in a series of famous researches noted for the clearness and power of the mathematical investigations, the aptness and skill of the experiments and the rapidity with which the whole was completed. Ampère's results laid the foundation of the modern system of measurement of currents of electricity and the international unit of current bears his name.

Another discovery connecting electricity with magnetism was made by Michael Faraday (1791–1867), Professor of Chemistry

* This relation between force and distance is referred to briefly as the " Law of Inverse Squares." The same relation or " law " applies to magnetic forces (also discovered by Coulomb) and gravitational forces (discovered by Sir Isaac Newton).

The importance of Coulomb's work is recognised by giving his name to the international unit of quantity of electricity.

at the Royal Institution, London*. It is not too much to say that the electrical engineering industry owes its existence to Faraday's discovery of the induction of electricity from magnetic forces which led ultimately to the invention of the dynamo, induction coil and numerous other appliances. The cost of producing electricity by the means previously available (chemical action or thermo-electricity—discovered by Seebeck in 1822) prohibited its use on the commercial scale made practicable by Faraday's discovery. One of the first machines for producing electricity by induction was made by Pixii. Others were constructed by Ritchie, Saxton, Clark, Von Ettinghausen, Stöhrer, Dove, Wheatstone, Siemens and others. Pacinotti first used the slotted armature (1860). The substitution of electromagnets for permanent magnets and the adoption of arrangements for making the machines self-exciting led to the production of the modern dynamo which may be said to date from Wilde's machine of 1867. The dynamos of Gramme, Brush and Siemens were among the first successful commercial machines.

Electricity was originally regarded as being probably an invisible material fluid of a subtle nature†. As electrifying a body was found to be without effect upon its weight, it was necessary to assume that the so-called electric fluid was imponderable, and the notion that electricity was in any sense of a material constitution was ultimately abandoned.

There was no real theory as to the nature of electricity until 1864, when James Clerk Maxwell (1831–1879) propounded his electromagnetic theory of light. Clerk Maxwell regarded each

* Faraday's researches in electricity are without parallel both for their importance and the brilliance of their execution. The following are all of the first rank: Induced electricity (1831), Identity of electricity from different sources (1833), Equivalents in electro-chemical decomposition (1834), Electrostatic induction—specific inductive capacity (1838), Relation of electric and magnetic forces (1838), The electricity of the Gymnotus (1839), Magnetic rotatory polarisation (1846). The method of representing magnetic (or electric) forces by means of "lines of force" is also due to Faraday.

† This view was quite natural two or three centuries ago when any unusual behaviour of either men or things was ascribed to the presence of humours or spirits, that is (from their point of view) fluids.

The modern use of the word "juice" for electricity is slang in its origin and not due to any theory of the constitution of electricity.

state of electrification of a conductor as corresponding with a state of strain in the luminiferous medium* surrounding it and that the change of strain accompanying a change of electrification was propagated through the luminiferous medium (as electromagnetic waves) with the velocity of light. Clerk Maxwell's prophetic vision was at first viewed with some scepticism owing to lack of corroboration from the experimental data then available to test it. However, in 1888 Heinrich Hertz (1857–1894) produced direct experimental proof of the existence of the electromagnetic waves predicted by Clerk Maxwell and laid the foundation of wireless telegraphy.

Still more recently the "Electronic Theory" has arisen. It is scarcely necessary to explain that these recent developments represent an addition to scientific knowledge and do not invalidate legitimate deductions drawn from the experiments of investigators holding older views but rather give them new forms of expression.

* Light has been infallibly proved to be a form of wave motion and as waves cannot be propagated through an absolute vacuity there must be (for instance between the sun and earth) some medium distinct from ordinary matter which transmits waves of light. This medium is called the luminiferous medium. It is also known by the name of the luminiferous ether or simply *the* ether.

CHAPTER II

CONDUCTION OF ELECTRICITY

Currents of Electricity.

Although electricity is not a material fluid, the meaning of the terms used in connection with the conduction of electricity can be best illustrated by analogy from the flow of material fluids. The use of the expression "current" for the transmission of electricity by conduction is due to analogy. The conception of currents of electricity and the principle applied to their measurement presents no difficulty. When once we have fixed up a system of measurement of quantities of electricity in terms of some unit of quantity, we can at once proceed to measure currents of electricity by the amount of electricity that passes in a given time, just as we can measure the rate at which gas or water is transmitted through a pipe in cubic feet per hour, gallons per minute or lbs. per second, etc. The unit of quantity of electricity in universal use* is called the coulomb, and currents are measured in coulombs per second. It so happens that in the case of electricity it is easier to measure currents than to measure quantities of electricity, so that it is convenient to have a separate single name for the unit of current. Unit current is called the ampere; one ampere = one coulomb per second.

* Fortunately in electrical measurements we are not plagued with the multiplicity of units to be found in ordinary weights and measures, but there are two recognised systems of units known as the electrostatic system and the electromagnetic system, both of which are based ultimately on the fundamental units of length, mass and time now universally adopted for scientific work, viz. the centimetre, gramme and second (C.G.S.). The electrical units in universal use for practical purposes are derived from the C.G.S. units of the electromagnetic system, but their relationships can be quite well understood without reference to their ultimate derivation. These units in general international use for practical purposes are the only ones which need concern us.

There are two respects in which currents of electricity differ from the flow of material fluids. Firstly, there is no connection between the amount of electricity conducted per second and the velocity with which the electricity travels along the conductor. Electricity always travels with the velocity of light, 186 000 miles per second. Secondly, negative electricity always travels in the opposite direction to positive electricity. As the amount of the negative current is always equal to that of the positive current, we ignore the negative in dealing with currents and take the direction of the current as that of the positive electricity and its amount as that of the positive electricity passing per second.

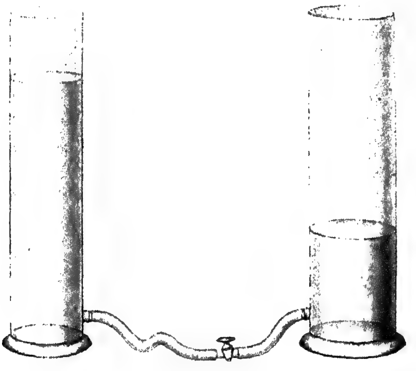


Fig. 2.

Similar remarks apply to the conduction of heat. Cold stands to heat in the same sort of relation that negative electricity does to positive, and when heat passes into a body, cold passes out of it, but in heat measurements we ignore cold altogether and only deal with heat quantities.

Potential.

Suppose we have two vessels containing water at different levels and a pipe by means of which we make a connection between them—as shown in Fig. 2—water will flow from the vessel in which it is at the higher level to the one containing water at the lower level, and the rate of flow (current) will be greater the greater the difference of level. Thus water would flow from the vessel represented on the left in Fig. 2 to the vessel on the right.

The rate of flow could be observed from the rate of change of position of the surfaces of the water. In fact, water flows from a place at a higher level to a place at a lower level at a rate depending upon the difference of level and the dimensions and arrangement of the pipe connecting the two places.

It is easy to see that corresponding to the pipe in the case of the flow of water, we have the conductor, wire or circuit in the case of electricity, and the amount of the current in any conductor depends upon the nature and dimensions of the conductor through which the current is passing. But there must also be something corresponding to the difference of level. The name "potential" is given to the electrical analogue of water level, and we see that electricity flows from a place at higher potential to a place at lower potential, the magnitude of the current depending upon the difference of potential and the nature and dimensions of the conductor between the two places.

Difference of potential has the same sort of determining influence on the flow of electricity that difference of level has on the flow of water, that difference of pressure has on the flow of gas, that difference of temperature has on the flow of heat.

Nature of Fluent	Quantity measured in	Current depends upon difference of	Current measured in
Water	Cubic feet, Gallons, etc.	Level	Cubic feet per sec., Gallons per min., etc.
Material fluids in general	Cubic feet, Gallons, Pounds, etc.	Pressure	Cubic feet per hour, etc.
Heat	Calories, British Thermal Units	Temperature	Calories per sec. B.Th.U. per sec.
Electricity	Coulombs	Potential	Amperes = Coulombs per sec.

Difference of potential is very frequently called Electromotive Force on account of its being regarded as the cause or force that moves the electricity. The terms electromotive force and difference of potential are strictly interchangeable wherever they occur, and sometimes the term "electric pressure" is used in the same sense. They are frequently written in the contracted forms, E.M.F. and P.D. respectively. The unit of electromotive force or difference of potential is called the volt.

Ohm's Law.

Let the difference of level or potential be maintained at a steady value E, and let the steady value which the current reaches be I*; then I depends upon E. In the case of water flowing through pipes I and E are not connected by any simple relation, but in the case of electricity flowing through conductors they are strictly proportional. This relation was discovered by Dr G. S. Ohm and is known as Ohm's Law†. The verification of this important law has been carried to extreme lengths by Chrystal.

If then we apply various differences of potential between the same two points on the same conductor and in each case note the

* In English books it has hitherto been usual to use the symbol C for current. There has been great diversity in the use of symbols not only between different countries but between different writers in the same country. The International Electrotechnical Commission which has been formed to secure uniformity of practice throughout the world in regard to electrical matters have considered, *inter alia*, the question of symbols, and the symbols used in this work are in accordance with the decisions they have so far published. See *International Symbols* published by Waterlow and Sons in Jan. 1914 (2*s.* 1*d.* post free).

† An interesting correspondence on the subject of Ohm's law appears in Vol. 62 of the *Electrician* (Dec. 5th, 1913 to Jan. 30th, 1914).

It is as well to caution the student against supposing that the modern forms of statement of "laws" of nature are necessarily the same either in words or in substance as those originally given by their discoverers. For example, it would be difficult to find a statement of the Law of Gay Lussac or Charles which was not to the effect that "The volumes of all gases at constant pressure increase by $\frac{1}{273}$ of their volume at 0° C. for each degree centigrade rise of temperature." This law arises out of a statement of Gay Lussac's to the effect that citizen Charles had informed him that he could find no difference in the expansibilities of different gases on heating them from the freezing point to the boiling point. The meagreness of the experimental apparatus at the disposal of "citizen" Charles renders it absolutely certain that the figure 273 never appeared in any statement of his.

In case the student may think that the modern version of a law is always an elaboration of the original, we mention another example, viz. Newton's Law of Cooling. Newton's original statement was to the effect that the rate of cooling of a body *in a steady current of air* was proportional to the difference of the temperatures of the body and the air. No recent statement of Newton's Law of Cooling contains the words in italics (if we except those of punctilious people like the late Professor Tait who had a gift for quoting Newton), and the literature of the subject abounds with discussions of the limitations of Newton's Law and questions are set thereon in examination papers, even since Dr Mitchell experimentally verified Newton's statement (over a wide range of temperatures).

steady value which the current reaches*, the corresponding values of difference of potential and current will be in the same ratio, that is, the quotients obtained by dividing each difference of potential by its corresponding current will all be alike.

In that case, E/I would be what mathematicians would call a constant, the value of which would depend on the nature and dimensions of the conductor between the two points. This constant is called its resistance. The unit of resistance is the ohm (so named in honour of the discoverer of Ohm's Law), and it is so chosen that when E is given in volts and I in amperes the resistance ($R = E/I$) is given in ohms†. We therefore have for any given conductor carrying a steady current of electricity

number of ohms = number of volts ÷ number of amperes ;
number of volts = number of amperes × number of ohms ;
number of amperes = number of volts ÷ number of ohms.

These relations are represented in algebraical form by the equations

$$\frac{E}{I} = R, \quad E = IR, \quad \frac{E}{R} = I, \quad \frac{I}{E} = \frac{1}{R}.$$

It sometimes happens that some quantity—such as a resistance for example—is either so very large or so very small that the figure representing it in ordinary units has a large number of ciphers, either before or after the decimal point. To obviate the use of such clumsy figures there is often used a decimal multiple or submultiple of the unit, as is done in the metric system of measurement generally, and the same prefixes are used as in the

* In ordinary circuits without special arrangements for prolonging the "rise" of the current, it reaches its steady value in a second or two or a fraction of a second.

† The ratio of I to E (or I/E, *i.e.* the reciprocal of R) is called the conductance of the conductor.

Conductance = number of amperes ÷ number of volts.
,, = one ÷ number of ohms.

Conductance is represented by the symbol G and its relations are shown in the following equations

$$G = \frac{1}{R}, \quad R = \frac{1}{G}, \quad \frac{I}{E} = G, \quad I = EG, \quad \frac{I}{G} = E, \quad \frac{E}{I} = \frac{1}{G}.$$

An International Congress, to be held at San Francisco in 1915, will consider the adoption of the name "Siemens" for the unit of conductance.

metric system to denote its relation to the unit proper. Thus a resistance of 32 000 000 ohms may be described as 32 megohms, the prefix meg (mega) indicating that the number represents millions of ohms; so also an E.M.F. of .0000092 volts may be written as 9.2 microvolts.

Electric Circuits.

Suppose we wanted to maintain a steady current of water in the apparatus illustrated in Fig. 2, we should require some device for keeping a constant difference of level between the surfaces of the water in the two vessels. In like manner, to maintain a steady current of electricity between two points on a conductor, we require something to keep a constant difference of potential between these points. A voltaic cell, or a battery of such cells, or a dynamo, can be used to obtain a more or less constant difference of potential between what are called its terminals. This difference of potential is spoken of as its "voltage." The terminal at which the (positive) electricity is regarded as leaving the cell or dynamo is called the positive terminal or positive pole; the other is called the negative. No current of electricity can be obtained unless the two terminals are connected by a complete conducting circuit*. When the circuit is completed it is said to be *closed*; if a break or disconnection is made in the circuit it is said to be *open*. If the terminals of a cell or dynamo are connected by a conductor of very small resistance it is said to be *short-circuited*. A switch is usually made to form part of a conducting circuit, and by this means the circuit can be closed or opened in a convenient manner without disturbing wires or terminals.

When a number of conductors are connected in such a manner that the same current must pass through them in succession, they are said to be connected in series. When a number of conductors are connected between two points so that the "main" current

* As air or empty space does not conduct electricity, it is obvious that a current of electricity cannot be maintained along a conductor which comes to a "dead end." The reason why a "return" conductor is always necessary for electric circuits and not required for gas or water supply is simply that the atmosphere is a non-conductor of electricity while it does not interfere with the passage of gas or water.

is subdivided amongst them, they are said to be connected in parallel. When one conductor is connected in parallel with another it is often spoken of as a "shunt." We may point out here that the *resistance* of a group of conductors connected in *series* is the sum of their individual resistances and that the *conductance* of a group of conductors connected in *parallel* is the sum of their individual conductances. (For proofs of these propositions and further particulars, see Appendix to Chap. II.)

Resistivity.

(*Specific Resistance.*)

When comparison is made of the resistances of a number of conductors of the same uniform material, it is found that their resistances are directly proportional to their lengths and inversely as their cross-sectional areas*. In comparing the resistance properties of different materials it is necessary to reduce the resistances to that of some standard size of specimen, and for such purposes unit length and unit cross-section are chosen as standards and the resistance of this size of specimen is called the resistivity† of the material of which it is made.

It is obvious that the resistivity of a substance may be defined as the resistance between opposite faces of a unit cube of the substance; hence resistivity is often briefly described as the resistance of unit cube, or even resistance *per* unit cube; but it is to be noted that *resistance is not proportional to volume*, although that might seem to be implied in the last form of statement.

The resistivity of a metal is determined by making it up into the form of a uniform wire or rod, whose resistance is determined by a suitable method. This resistance divided by the length and multiplied by the cross-section gives the resistivity. From this again the resistance of any other specimen of the same material can be calculated. As the numbers representing resistivities of metals in ohms per centimetre cube are very small, it is convenient to give them in microhms per centimetre cube. English engineers

* This relation was originally discovered by Ohm.

† The term "Specific Resistance" has been in common use for resistivity. The modern term, resistivity, is to be preferred for a variety of reasons.

usually prefer to work with dimensions in inches, and so resistivities are often given in microhms per inch cube*.

The following list gives the resistivities of some useful metals (in an annealed state, and at the common temperature 60° F. or 15.5° C.). Other resistivities will be found on page 15.

Metal	Microhms per cm. cube	Microhms per inch cube	Ratio to Copper
Silver	1.56	.615	.934
Copper	1.67	.658	1.00
Aluminium	2.84	1.12	1.70
Phosphor bronze	8.6	3.4	5.1
Iron	9.98	3.93	5.98
Platinum	11.54	4.54	6.91
Tin	13.94	5.49	8.35
Tantalum	16.3	6.42	9.76
Lead	21.7	8.55	13.0
German silver	22	8.7	13
Platinoid	42	16.5	25
Manganin	42	16.5	25
Eureka metal	47.5	18.7	28.4
Mercury	95.5	37.6	57.2
Bismuth	117.4	46.3	70.3

The resistance of any specimen depends not only on its dimensions and its chemical composition, but also on its temperature and physical state generally. Other things being the same, a metal has its lowest resistivity just after it has been annealed; the effect of stretching, bending, pressing, or in any way straining it, is to increase its resistivity. The effect of drawing annealed copper into wire is to add about 2 % to its resistivity. This will give an idea of the order of magnitude of the effect of strain upon resistance. Such addition can be removed again by subsequent annealing.

The resistance of a metal conductor increases as its temperature rises; the rate of increase is not absolutely uniform, but varies continuously with the temperature, and, of course, differs for

* It is obvious that, as there are 2.54 cm. (approx.) in an inch, number of microhms per inch cube

$$= \text{number of microhms per centimetre cube} \times \frac{2.54}{2.54^2}$$

$$= \text{number of microhms per cm. cube} \div 2.54.$$

different metals; generally, however, its amount is less than .6 % per 1° C. The effect of temperature on resistance is a matter of great practical importance. The rate at which the resistance of a specimen changes with temperature is called its Temperature Coefficient of Resistance.

Classification of Substances.

The distinction between a conductor and a non-conductor is somewhat arbitrary and vague. There is no substance which is a perfect conductor, if by that we mean a substance which offers no resistance to the passage of electricity; likewise, there is no perfect non-conductor in the sense of a substance which never allows any electricity at all to pass through it. The term conductor is applied to substances having simply a small or not very great resistivity, and the term non-conductor is applied to substances having a very large resistivity. Most mineral and organic compounds fall under the latter category.

Accurate investigation of the resistance properties of metals is comparatively easy, but great difficulty attends the determination of resistances of non-metallic substances. With regard to the latter, enough has been done however, to enable us to conclude that they differ from metals in the following respects:

(1) they do not all rigorously follow Ohm's Law,

(2) in any case they have immensely greater resistivities*,

(3) their resistances vary with temperature at greater rates,

(4) their resistances diminish with rise of temperature.

The temperature coefficient of substances whose resistance diminishes with rise of temperature is regarded as being negative, and is distinguished by the minus sign.

From the point of view of their resistance, substances may be broadly classified into the following groups: pure metals, alloys, solutions, mineral and organic compounds. The contrast of the resistance properties of these groups of substances is brought out in the following table.

* The terms resistance and resistivity are necessarily vague when applied to substances which do not follow Ohm's Law.

Group	Substance	Resistivity in Ohms per cm. cube	Temperature coefficient (Centigrade)
Pure Metals	Silver	.000 001 47	.004 00
	Copper	·000 001 56	·004 28
	Gold	.000 002 20	.003 77
	Aluminium	.000 002 66	.004 35
	Zinc	.000 005 75	.004 06
	Nickel	.000 006 93	.006 18
	Platinum	.000 010 92	.003 67
Alloys	Aluminium 94 %, copper 6 %	.000 002 90	.003 81
	Aluminium 94 %, silver 6 %	000 004 64	.002 38
	Gold 90 %, silver 10 %	.000 006 28	.001 24
	Copper 97 %, aluminium 3 %	.000 008 85	.000 897
	Copper 87 %, nickel 6½ %, aluminium 6½ %	.000 014 91	.000 645
	Copper 50½ %, zinc 31 %, nickel 18½%	.000 029 98	.000 273
	Silver 66 %, platinum 33 %	.000 031 58	.000 243
	Copper 84 %, manganese 12 %, nickel 4 %	.000 046 68	.000 0
Carbon	Incandescent lamp filament	.004	−.000 54
	Arc lamp carbon	.007	−.000 5
	Retort carbon	.067	
Solutions	Nitric acid (20 % at 24° C.)	1.3	−.014
	Ammonium chloride (sat. at 18° C.)	2.4	−.015
	Sodium chloride (sat. at 18° C.)	4.7	−.023
	Zinc chloride (30 % at 13° C.)	11.0	
	Tartaric acid (20 % at 20° C.)	100.0	−.019
	Acetic acid (20 % at 20° C.)	700.0	−.017
	Ordinary distilled water	about 10 000.0	
Mineral and organic compounds	Fused sodium nitrate	0.8	
	Fused zinc chloride	110.0	
	Pure alcohol	500 000.0	
	Purest obtainable water at 18° C. (distilled in vacuo)	4 000 000.0	
	Benzene	5 000 000.0	
	Flint glass (at 200° C.)	100 000 000 000.0	
	Bohemian glass	60 000 000 000 000.0	
	Mica	80 000 000 000 000.0	
	Gutta-percha	400 000 000 000 000.0	
	Flint glass at 60° C.	600 000 000 000 000.C	
	Vulcanised India rubber	2 000 000 000 000 000.0	
	Shellac	9 000 000 000 000 000.0	
	Ebonite	30 000 000 000 000 000.0	
	Paraffin wax	35 000 000 000 000 000.0	
	Porcelain	500 000 000 000 000 000.0	
	Air, at ordinary pressures, practically infinite.		

The resistivities given above for pure metals and alloys are for the temperature of 0° C. The figures given for these substances are taken from the results of the investigations of Fleming and Dewar (see *Phil. Mag.* Sept. 1893). The remaining data have been compiled from various sources and are only given in round numbers for obvious reasons.

Metals.

As will be seen on comparing the numbers given in the table, the effect of alloying a metal is to increase its resistivity. It is, however, in the present state of knowledge impossible to predict the resistance properties of an alloy from its chemical composition. Indeed, the order of the first two alloys on our list is hardly what would be expected; but the general conclusion which we have stated is warranted by all available data.

Even a small trace of another metal—it may only be an impurity—has a marked effect upon resistance; 1 % of impurity may sometimes add as much as 5 % or even 10 % to the resistance*. As it is important to have conductors of as low resistance as possible for "mains" carrying current for electric lighting and transmission of power, these invariably consist of copper refined by the electrolytic process which produces it of remarkable purity. The cost of silver, which is the only substance with a less resistivity, renders its use prohibitive.

Not only have alloys generally higher resistivities than pure metals, but their resistance increases less with temperature. In the case of most pure metals the resistance increases about .4 % per 1° C., but as will be seen from the table, most alloys increase much less than this. As regards the temperature effect alloys show greater variety than pure metals, but it may be taken as a general rule that the more complex an alloy is, the greater is its resistivity and the less its increase of resistance with temperature. Some alloys have actually been produced with resistance diminishing with rise of temperature (at some parts of the thermometer scale, at any rate).

In the case of the alloy manganin (copper 84 %, manganese 12 %, nickel 4 %) the temperature change of resistance is quite

* A striking illustration of this is afforded by the value of the resistivity of nickel obtained by Fleming and Dewar. The nickel they experimented upon was prepared by Swan by the electrolytic method which yielded a sample of phenomenal purity and its resistivity was about 40 % less than that of the specimen used by Matthiessen, although he, in his classic researches in this subject, worked with the purest samples obtainable in his time. Also in the case of bismuth, Fleming and Dewar obtained with their electrolytic specimen a value about 20 % less than Matthiessen's.

negligible at ordinary temperatures; hence it is extensively used in the manufacture of standard resistances, as no temperature correction is required for it. It is important to know that this alloy has to undergo a course of annealing processes (this treatment is known as "ageing") before its resistance properties reach a steady state. When this state has been reached its temperature coefficient varies continuously from + .000 025 at 0° C. to − .000 024 at 80° C. and higher temperatures, passing through the value 0 at about 35° C.

Among alloys which are (or have been) used in the construction of resistances may be mentioned, German silver (copper 50 % to 60 %, nickel 15 % to 20 %, zinc 20 % to 30 %), Platinoid (german silver + 1 % or 2 % of tungsten), Manganese Copper (copper 70 %, manganese 30 %), and Platinum Silver (silver 66 %, platinum 33 %). Others are Eureka, Constantan, Nickeline, Rheotan, Rheostene, Kruppin, Resista. Some of these are suitable for use in resistance boxes intended for accurate work; others are only good for regulating or starting resistances for motors and work of that class.

Non-metallic Solids.

Among non-metallic substances the only solid of any importance which has not a very high resistivity is carbon. In the table on page 15 we have put it by itself. Like all non-metals its resistance diminishes with rise of temperature; indeed, the resistance of the carbon filament of an ordinary incandescent electric lamp at the temperature of incandescence is only half that at ordinary temperatures; (whereas, the filament of a tantalum lamp has six times the resistance when it is incandescent that it has when cold).

Most other solid non-metallic substances have so high a resistivity that they are not reckoned as conductors of electricity at all, but as their resistance diminishes with rise of temperature, some of them have a moderately low resistivity at high temperatures. A case in point is the filament of the Nernst lamp, which is practically a non-conductor at ordinary temperatures, and requires to have its temperature raised by an auxiliary heater before it allows sufficient current through it to act as an illuminant.

Solutions.

Solutions—aqueous or other—which conduct electricity to an appreciable extent, are called electrolytes. The figures given in the table on page 15 will give an idea of the order of magnitude of their resistivities. The resistivity of every kind of solution diminishes with rise of temperature. The resistivity of a solution depends also upon the strength of the solution, being high for very dilute solutions : but it is not inversely proportional to the strength of solution.

The effect of impurities in a solution is to diminish the resistivity. This makes it almost impossible to determine how great the resistivity of absolutely pure water really is.

When electricity is produced by a " voltaic " cell (or battery—whether primary or storage) the current flowing from it has got to pass through the cell itself in order to complete the circuit. There exists therefore, in series with the " external " circuit, some resistance due to the cell which is spoken of as its " internal " resistance. The internal resistance of a cell consists chiefly of that of the fluids (*i.e.* electrolytes) in the cell ; and as the precise composition of an electrolyte in such circumstances changes during the passage of the current and also changes during periods of rest, we see that the internal resistance of a cell depends upon its past history and the current which is being taken from it at the moment. It also varies with temperature. It is not therefore constant but varies within limits. The electromotive force of a cell also varies within limits according to circumstances, and generally falls under conditions which cause the internal resistance to rise.

Insulators.

The vast majority of substances are of no practical value either as conductors or insulators, their resistivities not being low enough for the former, and not high enough for the latter—or they are unsuitable on other grounds. The use of insulating substances in electrical engineering is to provide a covering or support for conductors so as to prevent the leakage of electricity or its passage in undesired directions. It is not every substance having a high resistivity that is suitable for this purpose, for

reasons that we shall see presently. The mere loss of the electricity which leaks and therefore runs to waste is not the main consideration, it is the chemical decomposition and consequent destruction which leakage gives rise to that cause electrical engineers to take the most elaborate precautions to bring all leakage down to the utmost procurable minimum.

A supremely important requirement of an insulator is that it should not harbour moisture either on its surface or in its internal structure. Any water thus associated with the substance obviously cannot be anything like pure, and acts as a fairly good conductor; and even if the quantity is so microscopical that the resistance remains pretty high, the small amount of current which is transmitted by the moisture gives rise to decomposition products which attack the substance. The effect of that is to continually increase the conductance of the insulator until it ultimately breaks down entirely. This accounts for the use of porcelain and such "moisture repelling" materials in exposed situations.

Another important matter is that substances which are quite good enough insulators for a moderate difference of potential or voltage, may break down entirely at a higher voltage; just as a composition lead pipe which suffices for carrying ordinary coal gas at pressures of about 2 inches of water would be hopelessly inadequate to carry steam at 150 lbs. per sq. inch! Therefore it is necessary to adapt the quality and thickness of the insulation on a conductor of electricity to the voltage at which it is going to be worked.

The insulation on a conductor of electricity has to serve a similar purpose to the *pipe* which carries the supply of material fluids such as gas, water, steam, and in these latter cases pipes can be made of metal which is at one and the same time strong, tough and impervious to the fluid transmitted. In the case of electricity, metals are conductors, that is to say, they act the part of the cavity inside the pipe in the cases of water and gas, and the enclosing material for the electricity has to be made of one of a number of substances none of which have the satisfactory mechanical properties of metals. Air would be a good insulating material for electricity but for its liability to "burst" (which is what it does when sparking takes place). There is no one substance which

can be used satisfactorily as an insulator in all cases, and therefore one must use in each particular instance the substance least badly adapted to the circumstances.

The following list gives some of the most important insulating substances commercially, and the principal uses to which they are put. In addition to these a large number of insulating materials are manufactured for special purposes.

Material	Where chiefly used
Slate	Switch-boards.
Porcelain, vitrified earthenware	Insulating supports of telephone and telegraph wires, and "live" rails of electric railways.
Mica, micanite, and preparations of mica	Electrical machinery—insulating washers, tubes, lining of armature slots, etc.
Vulcanite, ebonite	Insulating washers, bushes, and such like.
Vulcanised indiarubber	Insulation of mains and cables.
Paper, Presspahn, and preparations of paper	Insulation of underground mains. Insulation of conductors in electrical machines.
Cotton, silk	Covering of copper wires.
Varnishes	Impregnation of cotton and other insulation to prevent access of moisture. (Baking is resorted to, after varnish is applied.)

The important ingredients of insulating varnishes are generally one or more of the following:

Resins—such as shellac or dragon's blood with suitable solvents.

Linseed oil. (Sometimes eucalyptus oil is used.)

Paraffin wax, with suitable solvent.

It is important that the ingredients of an insulating varnish should be free from organic acids.

APPENDIX TO CHAPTER II

Resistances in Series.

When a number of conductors are connected so that all the current flowing through any one has to pass through each of the others, they are said to be connected in series, and in this case the total resistance of the whole set of conductors is, as we shall presently show, the sum of their individual resistances. In Fig. 3,

which gives a diagrammatic representation* of three conductors arranged in series supplied with current from a single cell, let the resistances of the individual conductors which are connected in series be R_1, R_2, R_3, respectively, and let the potentials at their ends be V_1, V_2, V_3, V_4; then as each of these conductors is carrying the same current, call it I, we have by the definition of resistance,

$$R_1 = \frac{V_1 - V_2}{I}, \quad R_2 = \frac{V_2 - V_3}{I}, \quad R_3 = \frac{V_3 - V_4}{I}.$$

Let the resistance of these regarded as a whole be R, then, as the total difference of potential between the ends of the whole set of conductors is $V_1 - V_4$, we have

$$R = \frac{V_1 - V_4}{I}.$$

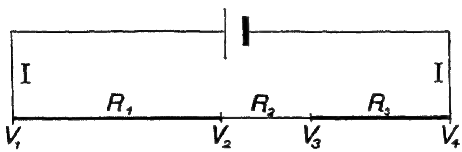


Fig. 3.

Now it is obvious that

$$\frac{V_1 - V_4}{I} = \frac{V_1 - V_2}{I} + \frac{V_2 - V_3}{I} + \frac{V_3 - V_4}{I},$$

so that finally we have

$$R = R_1 + R_2 + R_3.$$

We need hardly point out that although we have taken a particular case, the method of proof is perfectly general; and hence in every case we obtain the total resistance of any number of conductors in series by adding up their separate resistances.

* Such representations are called diagrams of connections; conductors are represented by lines, and the sign |ı represents the terminals of a cell, the long thin line being regarded as the positive terminal, the short thick line as the negative; the body of the cell is not represented—indeed, the same sign may often be found used to represent the terminals of a dynamo or other source of current supply. Fig. 4 shows a battery of three cells in the same manner. The method of representing other arrangements diagrammatically will be met with in diagrams occurring later.

It will also be seen that the "fall" of potential over each conductor is proportional to its resistance. This follows from the fact that

$$I = \frac{V_1 - V_4}{R} = \frac{V_1 - V_2}{R_1} = \frac{V_2 - V_3}{R_2} = \frac{V_3 - V_4}{R_3}.$$

By regarding it as a particular case of conductors in series, we can show that the resistance of a conductor of uniform section and material is proportional to its length; for if we have such a conductor carrying a steady current, the difference of potential between any pair of points a fixed distance apart will be the same all along it. This is obvious from considerations of symmetry*. Suppose then a uniform conductor divided up into any number of equal parts, n say, and apply the rule for the resistance of conductors in series to these several parts, and we at once get the

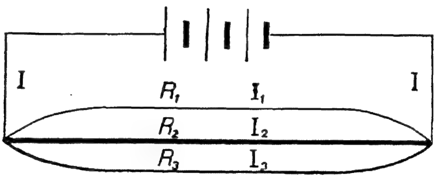


Fig. 4.

result that the resistance of the conductor is n times the resistance of an nth of its length, and therefore that the resistance is proportional to the length.

Resistances in Parallel.

When a number of conductors are connected between two points so that the current from the battery, or whatever the source may be, is subdivided amongst them, they are said to be connected in parallel. This is the arrangement shown in Fig. 4,

* It may be stated thus: the fall of potential along a uniform conductor is uniform. It is sometimes supposed that this is a *consequence* of Ohm's Law, but *it would be the case whether Ohm's Law was true or not.* The corresponding proposition in hydrodynamics is true, namely, that the fall of pressure along a straight uniform pipe, carrying a constant current of water, is uniform; but in this case the rate of flow is *not* directly proportional to the difference of pressure, thus deviating from the relation corresponding to Ohm's Law.

where three conductors having the individual resistances R_1, R_2, R_3, are connected in parallel, and the total current I from the battery is subdivided so that these resistances are carrying currents of amounts, say I_1, I_2, I_3 respectively. The difference of potential between the ends of each of these conductors is the same; call it E. Regarded as a whole, the total current in the combination of resistances is I, and the difference of potential E, so that if R be the resistance of the combination,

$$R = E/I, \quad \text{or} \quad I/E = 1/R.$$

Also, similarly

$$I_1/E = 1/R_1, \quad I_2/E = 1/R_2, \quad I_3/E = 1/R_3,$$

since

$$I = I_1 + I_2 + I_3,$$

we have

$$\frac{I}{E} = \frac{I_1}{E} + \frac{I_2}{E} + \frac{I_3}{E},$$

where E is the common difference of potential. Hence finally we have

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

This means that the conductance of a number of conductors in parallel is the sum of the conductances of the separate conductors; or, the reciprocal of the resistance of a combination of conductors in parallel is the sum of the reciprocals of their individual resistances.

In the particular case when there are only two conductors in parallel, the relation may also be put in the form:

$$R = \frac{R_1 \times R_2}{R_1 + R_2},$$

which gives the expression for the combined resistance of a conductor and its "shunt."

It is worth noticing that with conductors in parallel, the currents they carry are inversely proportional to their resistances. This will be obvious from the fact that

$$E = IR = I_1 R_1 = I_2 R_2 = I_3 R_3,$$

and therefore

$$I \div \frac{1}{R} = I_1 \div \frac{1}{R_1} = I_2 \div \frac{1}{R_2} = I_3 \div \frac{1}{R_3}.$$

EXERCISES ON CHAPTER II

Ohm's Law.

1. An incandescent electric lamp is observed to be taking a current of .225 ampere at a voltage of 232. What is its resistance in this condition ?

Answer. Resistance in ohms = E.M.F. in volts ÷ current in amperes
„ = 232 ÷ .225,
„ = 1030.

2. A galvanometer with a resistance of 60 ohms reads to 50 microamperes. What is the greatest E.M.F. one may apply to it ?

Answer. The greatest E.M.F. one may apply to the galvanometer is that which produces the greatest current which it reads, viz. 50 microamp. or .000 05 amp.

E.M.F. in volts = current in amperes × resistance in ohms
„ = .000 05 × 60,
„ = .003.

The required E.M.F. is .003 volt or 3 millivolts.

3. What is the current in a 25 ohm rheostat on a 220 volt circuit ?

Answer. Current in amperes = E.M.F. in volts ÷ resistance in ohms
„ = 220 ÷ 25,
„ = 8.8.

4. What must be the resistance in the circuit of a 20 volt battery when it is required to take a current of $2\frac{1}{2}$ amperes from it ?

5. How many storage cells (2 volts each) are required to produce a current of $5\frac{1}{4}$ amperes (as near as may be) in a coil of 3.8 ohms ?

6. A voltmeter, reading to 250 volts, has a resistance of 6000 ohms. What is the maximum current it has to be made to carry ?

7. The volts at the station end of a town supply are 228.5, the volts measured at a junction box at the same moment are 224.25 and the current in the mains at the same time is 184 amperes. Find the resistance of the mains between the station and the junction box. *Ans.* .0231 ohm.

8. What is the current produced by 110 volts in a resistance of 3.7 megohms ? *Ans.* 29.8 microamp.

9. What must be the resistance of a milliameter in order that it may be used to read volts ? *Ans.* 1000 ohms.

10. The field coils of an alternator are connected up to 220 volt supply mains, and they take a current of 1.95 amp. to begin with. After some time,

owing to the coils heating, the current finally settles down to 1.83 amp. Find the resistance of the field coils when cold and the increase of resistance due to the heating effect of the current.

11. A 16 c.p. carbon filament lamp, on a 220 volt circuit, takes .27 amp. When 10 volts are applied to the same lamp the current is .0063 amp. Calculate the resistance of the lamp in each of these two cases.

12. Which resistance is the greater, one that carries .5 amp. at 230 volts, or one that requires 28 millivolts to produce 60 microamperes in it ?

13. Find the E.M.F., current or resistance—whichever is not given—for each of the circuits to which the following particulars apply:

	E.M.F.	*Current*	*Resistance*
(*a*)	230 volts	500 amp.	—
(*b*)	4 volts	—	10 ohms
(*c*)	—	15 amp.	25 ohms
(*d*)	—	384 microamp.	1.3 megohms
(*e*)	4.1 millivolts	7.45 centiamp.	—
(*f*)	550 volts	—	10 megohms
(*g*)	—	1 milliamp.	1 megohm
(*h*)	110 volts	35 amp.	—

Resistances in Series.

14. What is the total resistance of a 20 ohm coil in series with a 30 ohm rheostat ?

Answer. In ohms, it is $20+30=50$.

15. A 10 volt battery is connected to a coil of wire in which it produces a current of 3.42 amperes. What resistance must be connected in series with the coil in order to reduce the current to 2 amperes ?

Answer. The resistance of the circuit with the coil as at first connected was $10 \div 3.42$ ohms, that is 2.92 ohms.

When the current is cut down to 2 amperes, the resistance in the circuit will amount altogether to $10 \div 2$ ohms, that is 5 ohms.

We only require to find the resistance which when added to 2.92 ohms will produce 5 ohms. The required resistance is therefore $5-2.92$ ohms or 2.08 ohms.

Note. The resistance of the battery itself (called its internal resistance) is in series with the resistance of the "external" circuit. In a case like the above the internal resistance of the battery does not enter into the calculation, as it forms part of the resistance in each case.

16. What is the total resistance of a circuit consisting of a coil of wire of 73 ohms resistance, a galvanometer of 210 ohms resistance, and 1110 ohms from a resistance box, all connected in series ?

17. A resistance box and a 476 ohm galvanometer are connected in series. To what resistance must the box be adjusted in order to make their total resistance 1000 ohms?

18. Find to the nearest tenth of an ohm the resistance which must be added in series with a 10 ohm coil, a 1 ohm milliameter, a wire of 28.71 ohms and another resistance of 36.42 ohms in order to make the total resistance as near as possible to 100 ohms. *Ans.* 23.9 ohms.

19. What current will an E.M.F. of 16 volts produce in a circuit consisting of two resistances of 5 and 3 ohms connected so that the current must pass through them in succession?

20. A milliameter with a scale of 150 divisions indicates one milliampere per scale division and has a resistance of 1 ohm. What resistance must be connected in series with it to enable the combination to be used as a voltmeter reading 2 volts per scale division? *Ans.* 1999 ohms.

21. The field coils of a dynamo take 2.59 amps. at 230 volts. A rheostat is put in series with the field coils which brings the current down to 2.14 amps. at the same voltage. Calculate the resistance of the rheostat.

22. A continuous current voltmeter has a resistance of 100 ohms and reads up to 1.5 volts. It is connected in series with a 900 ohm resistance coil to a battery and then indicates .98 volt. What is the actual E.M.F. of the battery? *Ans.* 9.8 volts.

Resistances in Parallel.

23. What is the resistance of the combination of a 60 ohm galvanometer with a 3 ohm shunt?

Answer. If the required resistance be R (in ohms)

$$\frac{1}{R}=\frac{1}{60}+\frac{1}{3}=\frac{21}{60}.$$

Hence $R=\frac{60}{21}=2.86$. The same result is also obtained thus:

$$R=\frac{60\times 3}{60+3}=\frac{180}{63}=2.86.$$

24. What is the resistance of a circuit containing resistances of 3.6 and 2.4 ohms in parallel? *Ans.* 1.44 ohms.

25. Find the resistance obtained in each of the following cases by connecting the given resistances in parallel:

(*a*) 4 ohms, 6 ohms.
(*b*) $\frac{1}{4}$ ohm, $\frac{1}{2}$ ohm.
(*c*) 1 ohm, $\frac{1}{9}$ ohm.
(*d*) 36 ohms, 4 ohms.

Miscellaneous Questions on Chapter II.

26. What current would flow through one mile of No. 18 copper wire if connected directly across the mains of a 100-volt circuit? Assume the resistance of 100 yds. of No. 18 to be 1.33 ohms. (C. and G. 1913*.)

27. A standard cell having an E.M.F. of 1.0183 volts is connected to a galvanometer through a resistance box set at 10.000 ohms. The deflection obtained is 35.2 scale divisions. Find the number of microamperes per scale division for that galvanometer. (Neglect resistance of cell and galvanometer.)

28. What is "specific resistance"? State the effect of temperature on the specific resistance of the following materials: German silver, copper, iron and carbon. What is the effect of temperature on the insulation resistance of the following materials: glass, indiarubber, paper as used for the insulation of cables, mica and marble? (C. and G. 1912.)

29. Mention the most important insulating materials used in electrical engineering, and discuss their suitability for specific purposes. (C. and G. 1911.)

30. Two conductors of equal length, and having resistances of 1000 ohms and 2000 ohms respectively, are connected in series to a secondary battery of 90 volts. Calculate the potential at the junction of the two conductors and prove it graphically. (C. and G. 1911.)

31. Draw up a table of the different classes of liquids, classified according to their power of conducting currents, giving examples of each class. How does a rise of temperature affect the conductivity of the different classes?

32. A field coil of a dynamo has a resistance of 850 ohms at 20 degrees centigrade. After the dynamo has been running for six hours the resistance increases to 908 ohms. What is the average temperature of the coil under this condition? The temperature coefficient of copper is 0.4 % per degree centigrade. (C. and G. 1912.)

Answer. Increase of resistance $= 908 - 850 = 58$.

Percentage increase of resistance $= \frac{58}{850} \times 100 = 6.83$.

Temperature rise in degrees centigrade $= \frac{6 \cdot 83}{0 \cdot 4} = 17.1$.

Temperature of coil (average, after six hours run)

$$= 20^\circ \text{ C.} + 17^\circ \text{ C.} = 37^\circ \text{ C.}$$

33. A battery of 10 volts electromotive force and 8 ohms resistance is connected to two resistances of 20 ohms and 30 ohms joined in parallel.

* Questions taken from Examination Papers of the City and Guilds of London Institute are indicated by the letters "(C. and G.)." The date given is the year in which the question was set.

Calculate the currents in the battery and in each of the resistances, and also the potential difference at the terminals of the battery. (C. and G. 1913.)

Answer. "External" resistance $=\dfrac{20 \times 30}{20+30}=\dfrac{600}{50}=12$ (ohms).

Total resistance of circuit $=8+12=20$ (ohms).

Current in battery = total current in circuits = E.M.F. of battery ÷ total resistance $=10 \div 20 = .5$ (amp.).

Potential difference at terminals of battery = total external current × external resistance = current in battery × external resistance $= .5 \times 12 = 6$ (volts.)

(The same result is also obtainable thus: Potential difference at terminals of battery = voltage of battery ÷ total resistance × external resistance $= 10 \div 20 \times 12 = 6$.)

Current in 20 ohms resistance = P.D. at terminals ÷ resistance $= 6 \div 20 = .3$ (amp.).

Current in 30 ohms resistance = P.D. at terminals ÷ resistance $= 6 \div 30 = .2$ (amp.).

34. Two wires in parallel, which have resistances of 2 and 4 ohms respectively, are connected to the terminals of a battery which has an electromotive force of 6 volts and an internal resistance of 1 ohm. Find the current in each of the resistances. (C. and G. 1912.)

35. Two resistances of 5 and 8 ohms respectively are placed in parallel and in series with this combination is a resistance of 4 ohms. If the potential difference between the extreme terminals is 100 volts, what will be the current in each resistance and the difference of potential between the terminals of each resistance? (C. and G. 1911.)

36. Show that when any number of resistances are connected in parallel, the resistance of the combination is always less than the smallest individual resistance used.

37. The resistance of 10 yds. of No. 18 Eureka wire is 3.72 ohms. Calculate the length of that kind of wire which has a resistance of 20 ohms.

38. What do you understand by the term "resistance" of a conductor? How is it affected by the length and section of the material? Give a list of as many metals and other substances as you can in the order of their resistances. (C. and G. 1911.)

39. In what respects do the electrical properties of non-metallic substances differ from those of metals?

CHAPTER III

MAGNETISM

General Properties of Magnets.

The science of Magnetism has resulted from the discovery of lode stone. A piece of lode stone, when suspended so as to be able to move freely, sets itself in a fixed direction. This property can be communicated to a piece of steel by stroking it with lode stone. Such pieces of steel are then called magnets, and their properties are said to be due to their possessing magnetism. The name magnet is derived from Magnesia, the ancient name of the district where lode stones were originally discovered.

Any piece of steel can be made into a magnet by stroking it with a lode stone or another magnet, and the piece of steel is then said to be magnetised. There are other ways of magnetising pieces of steel which will be mentioned later. Until recently the only substances known to be capable of being magnetised to any great extent were the elements: iron, nickel, cobalt, or substances containing one or more of these; hence these three metals are often spoken of as the magnetic metals*. Unless it is otherwise stated, in what follows it will be understood that the magnets referred to are of iron or steel.

* Most of the alloys and compounds of these elements are more or less "magnetic," but some are non-magnetic. Concerning non-magnetic alloys of iron, see Barrett, Brown, and Hadfield on "Researches on the Electrical Conductivity and Magnetic Properties of upwards of one hundred different Alloys of Iron"; *Journal of Inst. of Elect. Eng.* Vol. 31, pp. 674–729 (Feb. 1902). Or see *Electrician,* Vol. 48, p. 689.

Alloys of other metals with pronounced magnetic properties have recently been discovered. See Heusler, Starck, and Haupt. "On the ferromagnetic properties of alloys of non-magnetic metals," *Elwert,* Marburg, 1904. Or see *Electrician,* Vol. 55 (1905), page 94. Also see Fleming and Hadfield, "On the magnetic qualities of some alloys not containing iron," *Proc. Roy. Soc.* Series A, Vol. 79, No. A5io, July 1905. Or see *Electrician,* Vol. 55 (1905), page 329.

A piece of pure or fairly pure iron, or mild steel, however powerfully magnetised it may have been, soon loses nearly all its magnetism. The presence of impurities generally has the effect of enabling the iron to retain a greater amount of its magnetism. The magnetism so retained or left in the iron is called residual magnetism. Some brands of hard steel (containing tungsten) are made which retain their magnetism for any length of time without appreciable diminution. Such steels are admirably adapted for the manufacture of permanent magnets*.

If a long straight strip of steel is magnetised by stroking it along its length with another magnet, and then suspended by a thread so as to be free to move in a horizontal plane, it will set itself approximately in a north and south direction. If a number of such magnets are made they will all show the same property; and on every occasion on which they are suspended the same end of the magnet points northwards. The magnetism which the magnets are supposed to possess seems to be concentrated near the ends of such magnets. The small region occupied by the magnetism is usually referred to as the pole of the magnet, and sometimes this term is used to designate the magnetism itself. We can distinguish two kinds of magnetism or magnetic poles: the one which is at the northward end of a suspended magnet, and which is called positive; the other which is at the southward end of a suspended magnet, and which is called negative. The signs + and − are often used to distinguish these two kinds. A positive pole is frequently called a north pole, and a negative one a south pole.

It can easily be shown that like kinds of magnetism repel each other and unlike attract; the forces in all cases have been found to be inversely proportional to the square of the distance between the quantities of magnetism†. The force in any one

* It is convenient to have a term descriptive of brands of iron which retain insignificant amounts of residual magnetism and the designation "soft iron" is used for such. "Hard steel" is similarly used as a general term for brands which retain their magnetism well.

† The "law of inverse squares" for magnetism can be deduced from the experimental result that the magnetic force due to a "short" bar magnet, at any point in the line of its axis, is inversely proportional to the cube of the distance from its centre.

case depends upon the amount of the magnetism and the quantity of magnetism is taken to be proportional to the force. Unit quantity of magnetism is defined as that quantity which, situated at unit distance (1 cm.) from an equal quantity, repels it with unit force (one dyne). Hence the force (F) between two quantities of magnetism m and m', a distance d apart, is given by $F = m \cdot m'/d^2$. Unit quantity of positive magnetism concentrated at a point is called a unit pole.

The behaviour of the freely suspended magnet is explained by the presence of magnetism in the earth. Thus there is negative magnetism in the neighbourhood of the earth's geographical north pole, and positive magnetism in the neighbourhood of the earth's geographical south pole*. The mariners' compass† consists essentially of a magnet, or rather a set of magnets, mounted so as

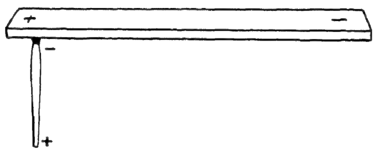


Fig. 5.

to be able to rotate freely in a horizontal plane, its indications being observed by the reading on a card to which the magnets are attached and which moves with them.

Magnets have the power of attracting pieces of iron and steel, and this is explained by supposing that the magnet "induces" a magnetic condition in the attracted piece of iron or steel which thus becomes a magnet—at least for the time being—with its magnetism arranged so that the opposite kinds of magnetism are nearest each other as shown in Fig. 5‡. This property can be used

* For a good account of the present state of the science of Terrestrial Magnetism, see A. Gray's *Treatise on Electricity*.

† The compass points about 16° west of the true north in this country. The direction in which the compass points gives us what is known as the magnetic meridian.

‡ The explanation in this case is closely analogous to the explanation of the attraction of an electrified body for a non-electrified one. Compare Fig. 5 with Fig. 1, Chap. I.

to show in a simple and obvious manner that, in a long thin magnet such as those referred to above, the magnetism is practically confined to the ends. Take a magnet and bury it among iron filings; on bringing it out of the filings again, it will be noticed that the filings adhere to it in two tufts round the ends.

Molecular Theory of Magnetism.

When a long thin magnet is broken it is found that fresh magnetic poles appear at the break, and we get two complete magnets. If these pieces are again broken fresh poles occur at each end exposed, as indicated in Fig. 6, and in every case the magnets so obtained have each a positive and negative pole, and the quantity of positive magnetism in each magnet is equal to the quantity of negative magnetism; and the same is true no matter into how many pieces the magnet may be broken.

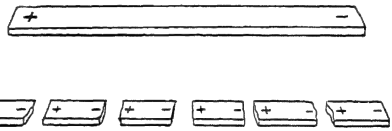


Fig. 6.

This points to the fact that each particle or molecule of a magnetic body behaves as a complete magnet in itself. This fact is the foundation of the molecular theory of magnetism. In the case of a body which is magnetised these molecular magnets are arranged with their + poles nearly all pointing one way, namely, in the direction of what is called the magnetic axis. In the interior of such a magnetised body, + and − poles come together, and any external force due to a + pole is neutralised by the equal and opposite force due to the adjacent − pole, except at the ends of the magnets, there being a surplus of "free" + poles at one end and a surplus of "free" − poles at the other. This accounts for the fact previously mentioned that the magnetism seems to reside at the ends of the magnets.

When these molecular magnets are arranged in straight parallel rows, the magnetic body is said to be uniformly magnetised, and the common direction of these rows of molecular magnets

is called the direction of magnetisation or of the magnetic axis, and this is the direction in which the body is said to be magnetised.

When a specimen of iron is not magnetised the molecular magnets must be so arranged that every + pole has a contiguous − pole, leaving no surplus of either kind of magnetism at any part. In this case these molecular magnets will obviously form series of closed chains (like strings of beads), the magnets in each chain being arranged with their + poles and − poles adjacent*.

When such a non-magnetised body is acted upon by any magnet the magnetic force tends to move the + poles of the molecular magnets in one direction and the − poles in the other. When the magnetic force is great enough to break up the molecular chains the body becomes magnetised. This explains how a magnet attracts a piece of iron or steel by means of the magnetic force magnetising it, and it also explains why the poles nearest each other of the magnet and piece of iron or steel are unlike.

We now see the reason why a specimen of pure iron does not retain its magnetism after the magnetic force is removed; it is that the molecules or particles can turn about fairly freely and so readily form themselves into chains again. It would seem that in the case of hard steel, *i.e.* iron containing a fair amount of alloyed impurity, the molecules or particles move or rotate with difficulty. This explanation is further borne out by the well-known fact that specimens which retain their magnetism are correspondingly difficult to magnetise. Further, magnetisation is accompanied by a slight change of volume† and a slight change in length. This is partly accounted for by the strain set up by the magnetisation, but after making allowance for this there is left over a surplus which may well be explained on the assumption that it is due to a change in the arrangement of the molecules‡.

* It is a common mistake to suppose that the molecular magnets of a non-magnetised body are assorted in a haphazard fashion, the mutual attractions of unlike poles and repulsions of like poles inevitably produce grouping in the form of closed chains.

† See C. G. Knott, *Trans. Roy. Soc. Edin.* Vol. 38, Part III, No. 13, and Vol. 29, Part II, No. 15.

‡ See E. T. Jones, "On the Magnetic Deformation of Nickel," *Phil. Trans.* A, Vol. 189 (1897), p. 189, and *Proceedings Roy. Soc.* Vol. 63, p. 44.

It is an obvious deduction from the molecular theory of magnetism that when all the molecules or particles of a magnetic body are all pointing with their + poles in one direction, the body cannot be magnetised any further. It is then said to be "saturated" or to have reached magnetic saturation. This phenomenon of saturation has long been known and forms strong confirmation of the molecular theory of magnetism.

A model, consisting of a large number of tiny magnets suspended so as to be free to rotate, has been constructed by Prof. Ewing for illustrating the behaviour of molecular magnets. In the model the magnetic force is applied by means of a current of electricity in a large solenoid surrounding the space occupied by the magnets. The closed chain formation of the unmagnetised body and the stages of the process of magnetisation are clearly shown in the model which provides the most conclusive evidence in favour of the molecular theory.

It may be here pointed out that to magnetise a piece of iron or steel in any direction it is only necessary to apply to it a sufficient magnetic force in the proper direction. Hence magnets are no longer made by the process of stroking which was mentioned above, as it is more convenient to place them between the poles of an electromagnet (see page 78).

Magnetic Field.

The region surrounding any magnet or any distribution of magnetism, in which the magnetic forces due to the magnetism are appreciable, is spoken of as its magnetic field, and the magnetic force at any point of a magnetic field is defined to be the force which would act on unit quantity of positive magnetism (unit pole) placed at that point (assuming that placing it there does not alter the distribution of magnetism producing the magnetic field). The magnetic force at any point in a magnetic field is called the (magnetic) field intensity at that point; and the direction of the force at a point is briefly described as the direction of the field at the point.

When the magnetic force is the same at all points of a magnetic field—both in direction and magnitude—the field is said to be uniform. In no actual case is any magnetic field absolutely

uniform throughout, but it is easy to produce magnetic fields which are exceedingly near to being uniform over a portion of space. The earth's field at any place at some distance from iron, magnets, or magnetic matter, may be taken as an instance of a uniform field. A uniform field in which the magnetic force or field intensity is everywhere unity—(one dyne)—is described briefly as a uniform unit field.

The direction of a field may be determined experimentally with fair accuracy by placing a small freely suspended lozenge-shaped magnet there. The direction will be approximately that of the axis of symmetry of the small magnet when it comes to its position of equilibrium. If it is allowed to oscillate in this position the field intensity may be calculated from its period of oscillation which is inversely proportional to the square root of the field intensity*.

The most convenient way of producing magnetic fields for practical or experimental purposes is to obtain them by means of currents of electricity in suitably arranged coils of wire.

Lines of Force.

A simple and ingenious method of representing graphically the magnetic force throughout a magnetic field by means of lines of force was devised by Faraday. These lines of force are supposed to be drawn so that the tangent of the line passing through that point gives the direction of the magnetic force at that point, and so that the number of lines per unit area measured in a plane at right angles to the tangent gives the numerical value of the force†.

These lines may be imagined to be the path traced out by an infinitely small magnet which is placed in the magnetic field and moved continuously in the direction of its magnetic axis (given by the direction in which it points), taking care that it is always in its position of equilibrium at every instant. Every one of such lines of force commences at an element of positive magnetism and forms a continuous curve ending in an element of negative magnetism.

* It is not practicable to make accurate determinations of field intensities by this method. In practice there is used either the bismuth spiral method or a ballistic galvanometer and exploring coil.

† That it is possible for lines to be arranged to do all this is a consequence of magnetic forces following the "Law of Inverse Squares."

In the case of a uniform field the lines of force are parallel and equidistant straight lines. The field intensity is then the number of lines which pass through a centimetre square placed perpendicular to the lines. Fig. 7 shows a section containing the lines of force in the magnetic field of a bar magnet (alone), and Fig. 8 shows the same for a bar magnet in the earth's field.

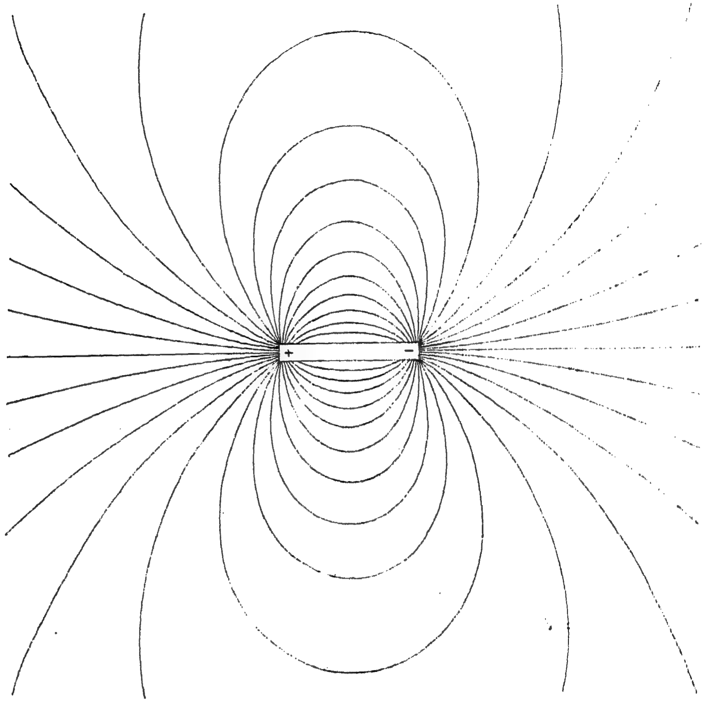


Fig. 7. Lines of Force of Bar Magnet (alone).

If a bar magnet is placed underneath a large sheet of cardboard and iron or steel filings are dusted over the top, tapping the cardboard gently enables the filings to set themselves with their longest dimensions along the lines of force. This serves to show in this case the general shape of such lines, and this device may be used to get an idea of the arrangement of the lines of force in other cases.

One important principle can be illustrated most conveniently by this means. It is that when a piece of soft iron is placed in a magnetic field, it has the effect of drawing the lines of force

into it (more or less). This is a consequence of the manner in which the induced magnetism is arranged. To see this effect, it

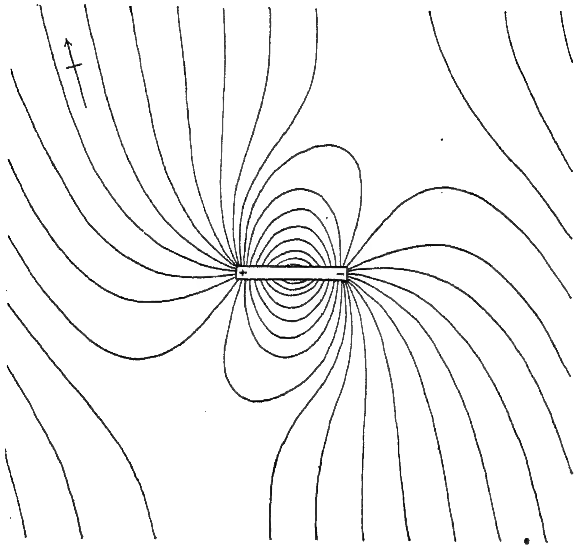


Fig. 8. Lines of Force of Bar Magnet in Earth's Field.

is only necessary to compare the appearance of the filings with a fixed arrangement of magnets (1) without, (2) with a piece of soft iron placed near them.

Induction and Permeability.

By means of lines of force one can obtain a complete map of the arrangement of magnetic force in a magnetic field but when the field happens to contain one or more pieces of iron (or other magnetic substance) the lines of force by themselves are not sufficient to supply full information as to the magnetic state of affairs in the interior of the iron. However, this further information can be obtained by additional lines which, for the present, we shall describe as "return" lines from the nature of the position they occupy.

The return lines are obtained by joining the ends of the lines of force entering and leaving the iron by lines following the tracks of the rows of molecules producing the corresponding elements of "free" magnetism. These return lines will therefore map out the

magnetic state of the iron and when the magnetisation is uniform these lines will be parallel and equidistant.

The return lines through the iron possess certain properties in common with lines of force (except that they are not to be included in measuring magnetic force by the number of lines per square centimetre) and it is necessary to have some name which will describe lines in such a manner as to indicate definitely whether they are included or not. We therefore use the term "lines of induction" when we desire to make it plain that these return lines in the iron are to be included as well as lines of force.

The *total* number of lines of induction per square centimetre in a specimen is called the *induction* and is represented by the symbol B. For engineering purposes it is generally sufficient to know the relationship for the materials used of the induction (B) to the magnetic force* (H) required to produce it. These are not proportional (except for air and non-magnetic substances for which obviously $B=H$), and their relationship is generally shown by means of a curve, called an Induction Curve. The explanation of the experimental determination of such curves is beyond the scope of the present volume, but their features will be seen on reference to Fig. 9†. It should be mentioned that variations

* In this connection magnetic force is usually spoken of as magnetising force, but the two terms are synonymous.

It is to be noted that the effective magnetic force acting upon a piece of iron placed in a magnetic field is not necessarily only the magnetic force produced by the external magnetising agents (which may be permanent magnets or suitably arranged electric currents) but is the resultant of this force and the force produced by any "free" magnetism induced on the iron; in fact, the magnetising force is the magnetic force which would exist in the space occupied by the iron if the iron were removed without disturbing the external magnetising agents and the "free" magnetism induced on the iron itself.

It is also to be noted that iron may be magnetised without producing "free" magnetism upon its surface. This may readily be the case when an iron ring is magnetised in a direction parallel to its periphery. In such a case an infinitesimally narrow crevasse (saw-cut) may be imagined cut across the iron perpendicular to the direction of magnetisation in order to obtain the means of arriving at the lines of induction; in fact, the induction is usually defined as the magnetic field intensity in such a narrow crevasse.

† The fact that the induction includes not only the "return" lines but also the lines of magnetic force in the space occupied by the iron, accounts for the fact that the Induction Curves are not horizontal even when the iron is saturated. In fact, if I be the magnetisation, $B=H+4\pi I$.

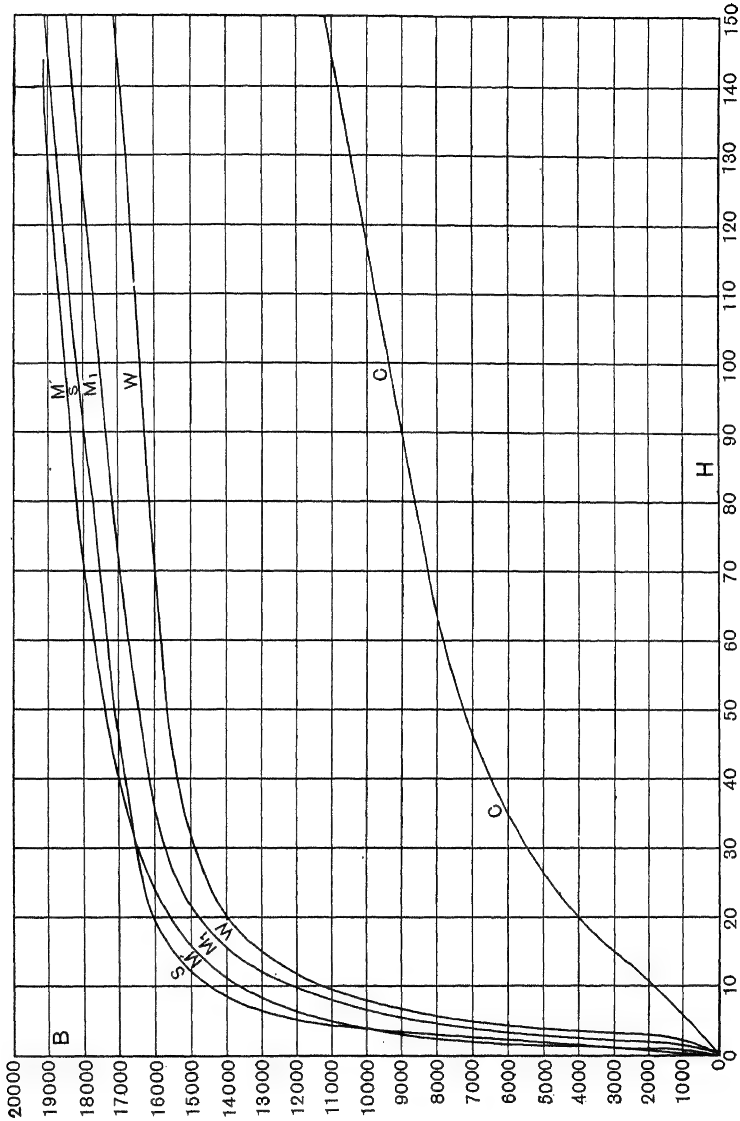


Fig. 9. Induction Curves.

S = Sankey's "Lohys" brand of iron.

M' = Upper limit} of various brands of field magnet steel.
M_1 = Lower limit}

W = Wrought iron.

C = Cast iron.

between different samples and brands will be met with, particularly in respect of cast iron.

The ratio of the induction to the magnetic force producing it is called the permeability of the material. (The symbol μ is used to represent permeability; $\mu = \frac{B}{H}$.) The permeability of a magnetic substance is not a constant quantity but varies with either B or H; it has, however, a maximum value which is understood to be referred to if we mention permeability without specifying any particular value of it. This maximum permeability occurs about the point indicated by the "knee" of the induction curve.

The following table gives the permeability of Sankey's Stalloy brand of iron which is extensively used in this country for armature cores, in the form of thin stampings.

Sankey's Stalloy Stampings.

Magnetising Force H	Induction B	Permeability μ
0.7	1500	2140
1.0	3300	3300
1.4	5000	3570
1.8	6500	3610
2.5	8100	3240
4.0	10 700	2675
5.0	11 750	2350
7.5	13 250	1770
10.0	14 000	1400
12.5	14 450	1155
15.0	14 800	985
20.0	15 400	770

The number of lines of induction passing through an area is often called the "flux" through it. The induction may also therefore, be described as the flux per square centimetre. (In older text-books flux is sometimes described by the term "total induction.") It is often convenient to measure flux in kilolines or in megalines (1 kiloline = 1000 lines, and 1 megaline = 1 000 000 lines).

CHAPTER IV

CURRENT MEASUREMENT

Magnetic Effects of Currents.

Currents of electricity might be measured by means of either (1) their magnetic effects, or (2) their chemical effects, or (3) their heating effects. All of these three effects have applications in the practice of current measurement but, for very efficient reasons, (1) is adopted as the *basis* of all current measurement. For one thing, the adoption of (2) or (3) as the basis of current measurement would involve the element of time as a necessary part of the measurement but, in any case, it is the magnetic effects of currents of electricity that enable us to accomplish simultaneous and instantaneous measurement of current and give electrical science an exclusive advantage in respect of measurements without parallel in other sciences.

It is easy to show experimentally that in all cases a current of electricity produces a magnetic field depending on the current and the arrangement of the conductor. With any fixed arrangement of the conductor, the magnetic field intensities at different points vary in the same proportion when the current is changed, and we measure the current by taking it as directly proportional to the field intensity (magnetic force) at any convenient point of the field. The researches of Ampère have supplied us with the means of calculating the magnetic force at any point in terms of the dimensions of the conductor and the unit of current when once it has been defined—and therefore also of determining the current when the magnetic force is measured. (The mathematical processes involved in such calculations need not concern us here.)

Tangent Galvanometer.

For many years, the principal instrument used for measuring currents of electricity was what is known as the Tangent Galvanometer*. This consisted essentially of a circular coil of wire or a set of circular coils of wire arranged along a common axis, with a small magnetic "needle" mounted in the axis of the coil or coils with pointer and degree scale or other appliances for reading its deflections. See Fig. 10. In use, the coils were set in vertical

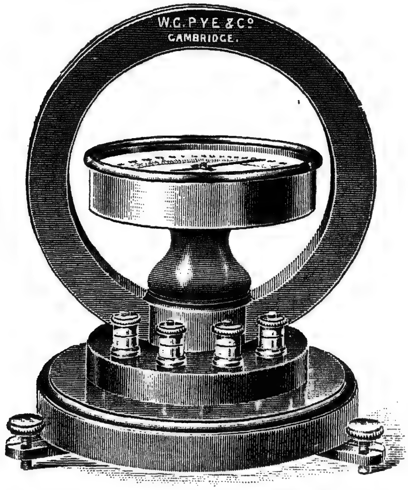


Fig. 10. Tangent Galvanometer.

planes through the magnetic meridian, and the needle was free to move about a vertical axis. If a diagram were to be constructed of the forces acting on the needle when a current is passing through the coils it would be seen that the ratio of the magnetic force produced by the current and the horizontal component (H) of the earth's magnetic field intensity is proportional to the tangent of the deflection of the needle. Hence, if H be constant, the current is proportional to the tangent of the deflection produced on the needle.

* The names galvanometer, amperemeter, and ammeter are all used to apply to instruments for measuring currents of electricity. The name galvanometer is the one most generally applied to the more delicate instruments used for laboratory work.

For the absolute measurement of current the tangent galvanometer has the advantage that it is easy to arrange the coils for accurate measurement and convenient calculation of the magnetic force per unit current acting on the needle. It is, however, necessary to know the horizontal component (H) of the earth's magnetic field (which can be found by experiment) when so used, and in any case it labours under the disadvantage that H is not constant for all time even at one place, and is, moreover, affected by any change in position of neighbouring magnets or pieces of iron; hence many precautions are necessary. Then there are occasional magnetic storms during which the variations of H are so rapid and capricious that the use of the tangent galvanometer is hopeless while they last. Such inconveniences were tolerated, but the general adoption of electric tramways in towns, with the perpetual disturbance of inevitable earth currents, led to the complete abandonment of the ordinary tangent galvanometer for serious work*.

Consequentially modern current measuring instruments have undergone a considerable amount of "specialisation of function." The ammeters which are used for the regular work of current measurement are generally of a type which is not affected by "stray" magnetic fields, earth currents, and such like, but give the same reading for the same current on every occasion. It has, however, to be graduated or calibrated by comparison with a "standard" instrument, that is, one arranged so that the current is capable of being calculated from its reading without the intervention of another ammeter. Such standard instruments are generally less convenient to use, but of course are only required for the purpose of "calibrating" others.

The student will be able to understand descriptions of the various types of modern current measuring instruments much more easily if he has a good general idea of the nature of the magnetic forces produced by currents in various arrangements of coils. This we proceed to give by showing the shapes assumed by the

* It is still convenient, however, to use it "backwards" as a means of determining H, by sending a known current through it. The "mirror" forms of galvanometer working on the same principle are still used where great sensitiveness is required (generally, however, with "permanent magnet control," and sometimes arranged "astatically").

lines of force in certain important typical instances—in addition to other necessary explanatory matter.

Magnetic Fields due to Currents.

The magnetic field produced by a current in a straight wire must obviously be symmetrical with respect to the wire and

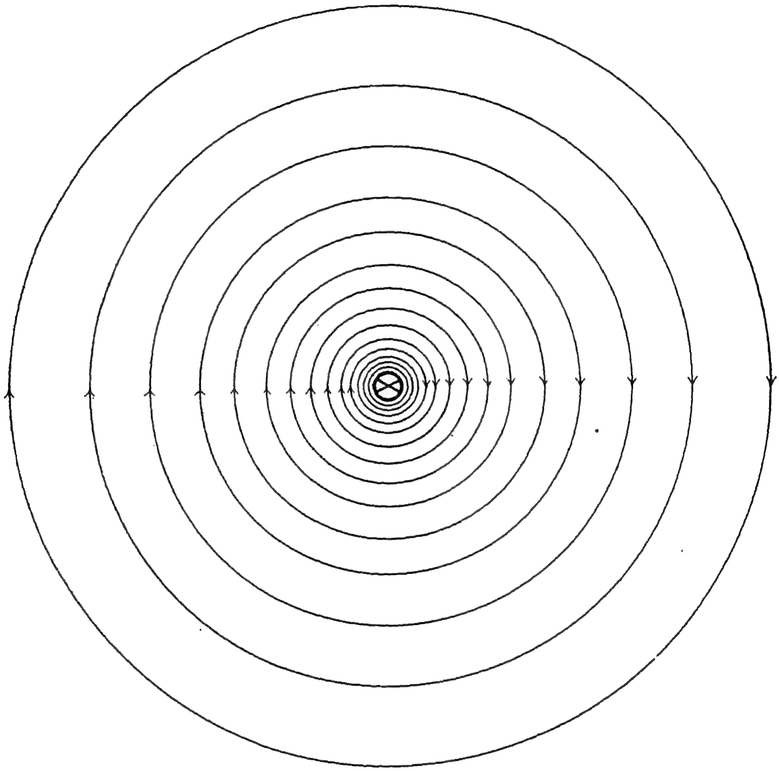


Fig. 11. Lines of Force of Current in Straight Conductor.

(since it happens that the direction of that component of the magnetic force produced by the current in any short piece of a conductor is at right angles to that part of the conductor) the lines of force in this case are circles with the wire as centre, as shown in Fig. 11*.

* In diagrams such as Figs. 11, 12, 13, when it is required to represent a current flowing at right angles to the plane of the paper, the sign ⊙ will be used to represent

The effect of bending the wire is to crowd the lines more or less on the side towards which the wire is bent. When the wire takes the form of a circular loop the lines of force have the shape shown in Fig. 12.

When the wire carrying the current is made up of a helical coil of several turns arranged in the manner obtained by winding it uniformly on a circular cylinder, the portions of the lines inside the coil become more and more nearly straight as the length of the

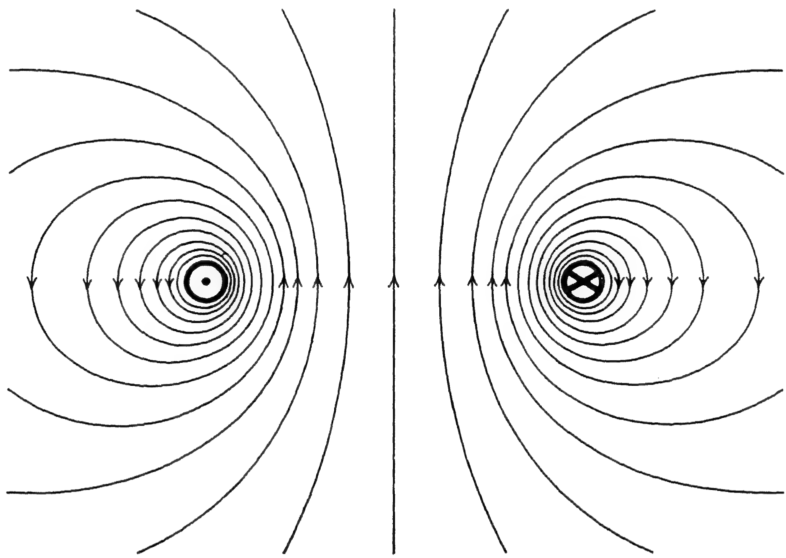


Fig. 12. Lines of Force of Current in Circular Loop.

coil is increased. This arrangement of a wire or conductor goes by the name of solenoid, and is illustrated in Fig. 13.

We may mention here that when a uniform magnetic field is

a current flowing upwards, and the sign ⊗ to indicate a current flowing downwards. The meaning of these signs may be remembered by regarding them as standing for the point and tail respectively of an arrow. Directions in the plane of the paper will be indicated by arrows in the usual way.

The arrows shown on the lines of force indicate the direction in which positive magnetism would be urged.

The general relation between the positive directions of the current and lines of force may be readily remembered from the fact that they are those of the direction of travel and rotation of an ordinary (right-handed) screw.

required it is obtained nowadays by using a current in a solenoid having a length of from 10 to 100 times its diameter.

The resemblance between Fig. 7 and Fig. 13, as regards the field external to the coil, is obvious, and shows that as regards external magnetic forces, a coil of wire carrying a current behaves very much like a magnet with its magnetic axis coinciding with

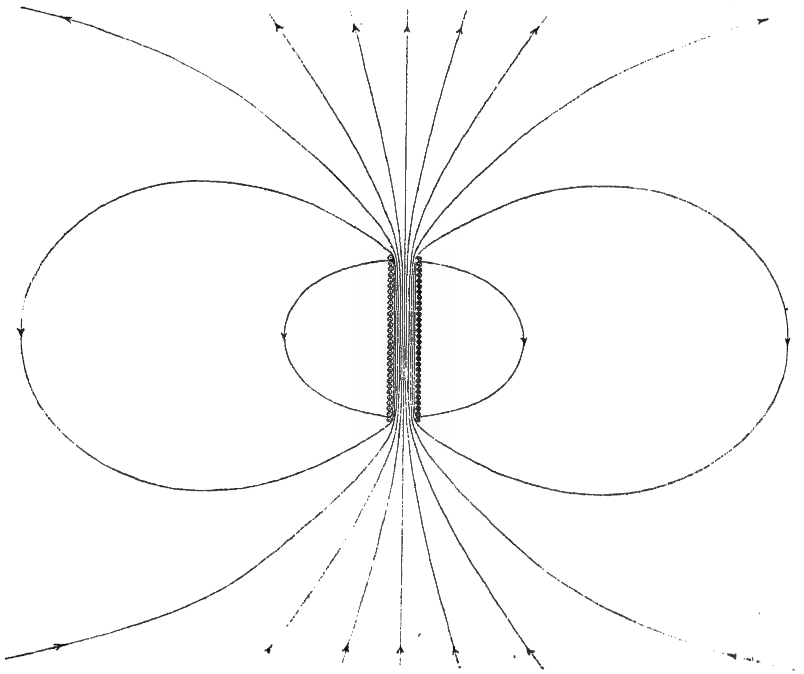


Fig. 13. Lines of Force of Current in Solenoid.

the axis of the coil. This principle is of great importance and we shall have occasion to use it frequently in the remainder of this chapter.

It can at once be inferred from this that a coil carrying a current will be acted on by the magnetic force produced by a magnet or a current in another coil. Also when two coils, each carrying a current, are placed with their axes in line, there will be attraction between them when the currents are going round in the same direction, and repulsion when the currents are going

round in opposite directions. This will be rendered clearer on reference to Fig. 14 which gives a sectional view through the common axis of three coils placed in line, and in which the equivalent magnets are indicated in dotted outline*.

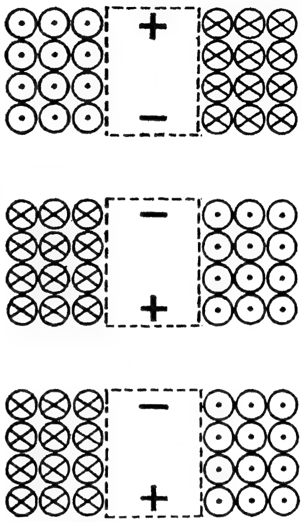


Fig. 14.

As the field intensity at any point due to a current is proportional to the current, and that due to a magnet is proportional to its magnetisation, the effect of varying a current in a coil can be reproduced in the case of its equivalent magnet by a proportional change in the magnetisation. This shows that the forces of attraction or repulsion between coils—such as is represented in Fig. 14—will be proportional to the current in each coil, and therefore proportional to the product of the currents. Hence the attraction or repulsion between two separate circuits carrying the same current, or between two separate parts (in series) of one circuit, is proportional to the square of the current. The measurement of current by means of the forces between coils is taken advantage of in certain standard instruments, in which it is desired to get rid of the use of magnets, and the consequent difficulty of measuring their magnetisation with accuracy, and uncertainty as to their constancy.

The relation between the dimensions of circuits and the forces between them due to currents they are carrying was also investigated by Ampère whose results enable the forces to be calculated in any given case. Such calculations are generally laborious

* It is possible to arrange a magnet which will produce absolutely the same field at every point as a current in a coil. The magnets shown by the dotted line in Fig. 14 are made smaller in cross-section than the precise equivalents of the coils would be; this is done for the sake of keeping the illustration clear, and it is quite accurate enough for the purpose of elucidating the points mentioned in the text.

mathematical undertakings. If, however, the force between two coils be observed for some one known current, all other currents can be easily obtained from the corresponding observed forces by the proportions of their square roots.

Forces on Conductors carrying Currents in a Magnetic Field.

Another principle which is applied in the construction of current measuring apparatus (and which has many other important applications in electrical engineering) can be deduced in a fairly obvious manner by regarding the foregoing matters from another point of view. This principle is that there is a force acting on a conductor carrying a current when it is in a magnetic field, whether the field is produced by magnets or other currents, or even the same current in other parts of the circuit. This will be obvious from the proposition already mentioned that a circuit carrying a current of electricity is equivalent in its magnetic effect to some corresponding magnet, and it will likewise be obvious that the force acting on the conductor is proportional to the current in it and to the field intensity of the magnetic field it is in.

It has no concern with our present purpose, but we should like to point out that we have here the kernel of the explanation of the action of an electric motor. Part of the current supplied to a motor goes to produce a magnetic field by means of the "field magnet" of the motor; in this field there is an arrangement of conductors mounted on an "armature" or "rotor"; current is also sent through these conductors which are then acted upon by forces which are transmitted to the shaft.

Current Measuring Apparatus.

Modern current measuring instruments may be classified in two entirely different ways, (1) according to their external form which depends chiefly upon the uses for which they are intended, (2) according to the principles applied in their internal construction.

These remarks also apply to instruments for measuring differences of potential, *i.e.* voltmeters. Indeed, for every type of ammeter

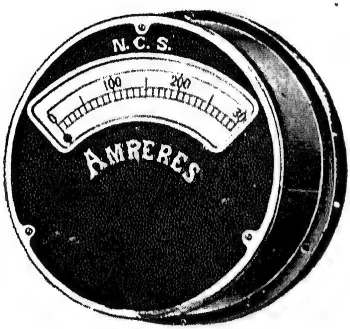


Fig. 15.

Fig. 16.

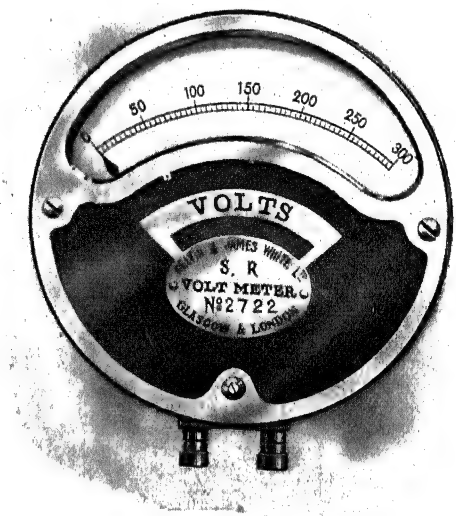


Fig. 17.

there is a corresponding type of voltmeter. All that is necessary to convert an ammeter into a voltmeter is to modify it so that (1) its resistance remains constant throughout the varying conditions of its use making the differences of potential between its terminals proportional to the current it indicates, (2) its resistance is so high that even the greatest current that it takes will be so small that it will not appreciably alter the amount of the current in the circuit subjected to measurement, (3) the scale is marked to show the volts corresponding to the current through it, instead of the current itself.

Classification of Instruments according to the nature of their use.

Form of instrument	How used
Standard instruments	For calibrating others.
Switchboard instruments:	For use on switchboards, and such places where they will be fixtures.
Circular pattern,	
Sector or thistle pattern,	
Edgewise pattern,	
Recorders	
Portable Instruments	For general laboratory and testing work.
Mirror galvanometers	Used when great sensitiveness is required.

Standard instruments form a separate category by themselves, and will be dealt with later (pages 69 *et seq.*). The differences between the other forms given in this list do not depend on any difference in the principles on which their action is based, but are almost entirely a matter of the arrangement of the pointer and scale and the external case.

Various forms of instruments adapted for use on Switchboards are illustrated in Figs. 15–23. The circular pattern (Figs. 15–17) takes its name from the shape of the case.

The sector pattern admits of a longer scale in proportion to the size of the case of the instrument. (See Figs. 18 and 19.) In many of the sector instruments the scale projects beyond the rest of the instrument, and by placing lamps behind it the scale can be illuminated so as to facilitate observations at night. "Illuminated dial" instruments are usually of the sector form or edgewise form.

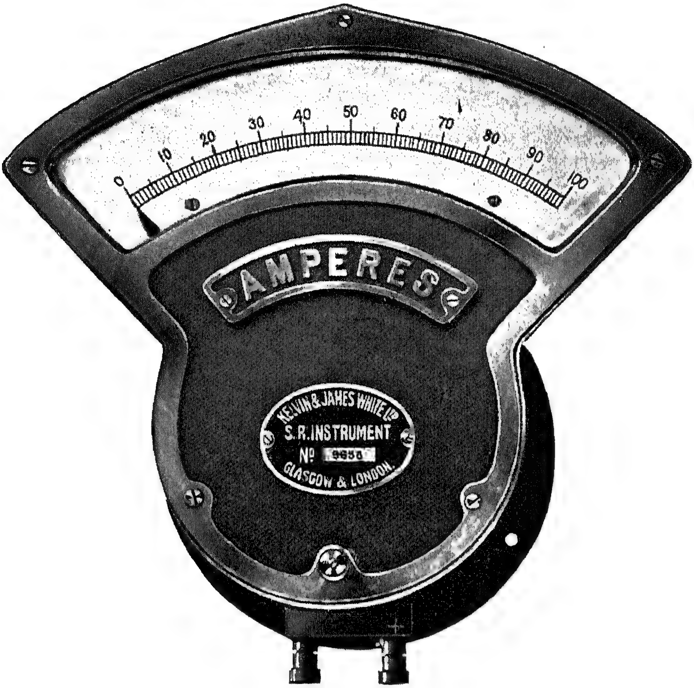

0
10
20
30
40
50
60
70
80
90
100
AMPERES
KELVIN & JAMES WHITE LTD
S.R. INSTRUMENT
Nº
GLASGOW & LONDON.

Fig. 18.

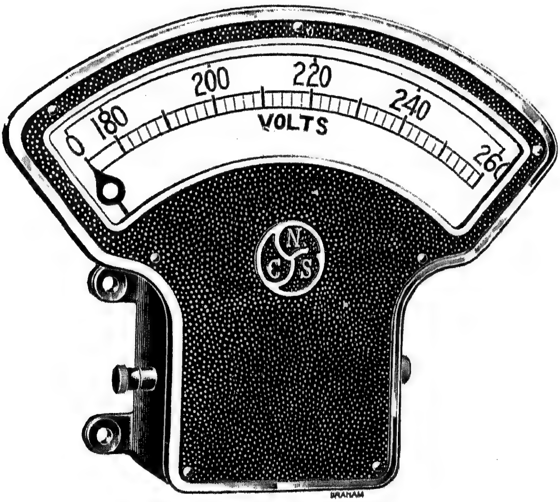

0
180
200
220
240
260
VOLTS

Fig. 19.

If the sector pattern instrument had the scale put on the edge and were turned to make it face the proper way we would get the edgewise pattern which is useful when it is necessary to economise space in a horizontal direction. When it is necessary to place instruments high above the line of the eye, edgewise instruments can be used with the scale tilted forwards. Figs. 20 and 21 illustrate edgewise instruments, the latter showing an illuminated dial pattern, the lamp of which is concealed under

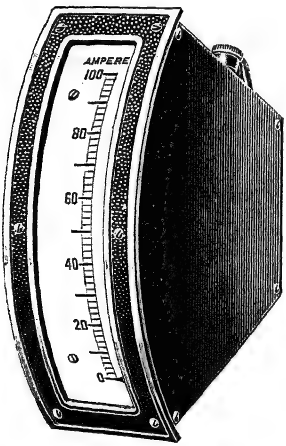


Fig. 20.

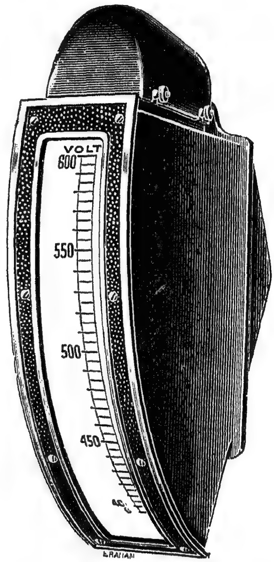


Fig. 21.

the cover. Occasionally edgewise instruments are made with the scale horizontal.

Recording ammeters and voltmeters are used for the purpose of obtaining a record of the fluctuations of current or E.M.F. over a period of time. A drum driven by clockwork (or otherwise) carries a paper appropriately ruled which takes the place of the scale of an ordinary instrument, and the tip of the pointer is adapted to act as a pen. A new paper requires to be inserted when the old one is used up. Recorders have often given trouble from various causes. A good deal of inventive skill has been

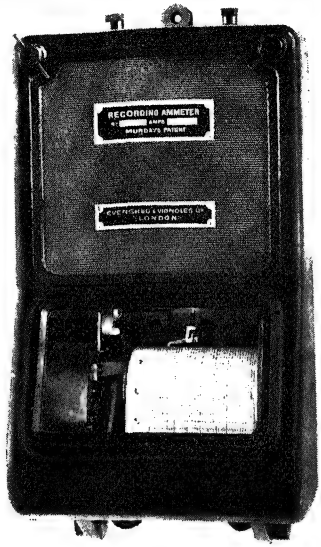


Fig. 22.

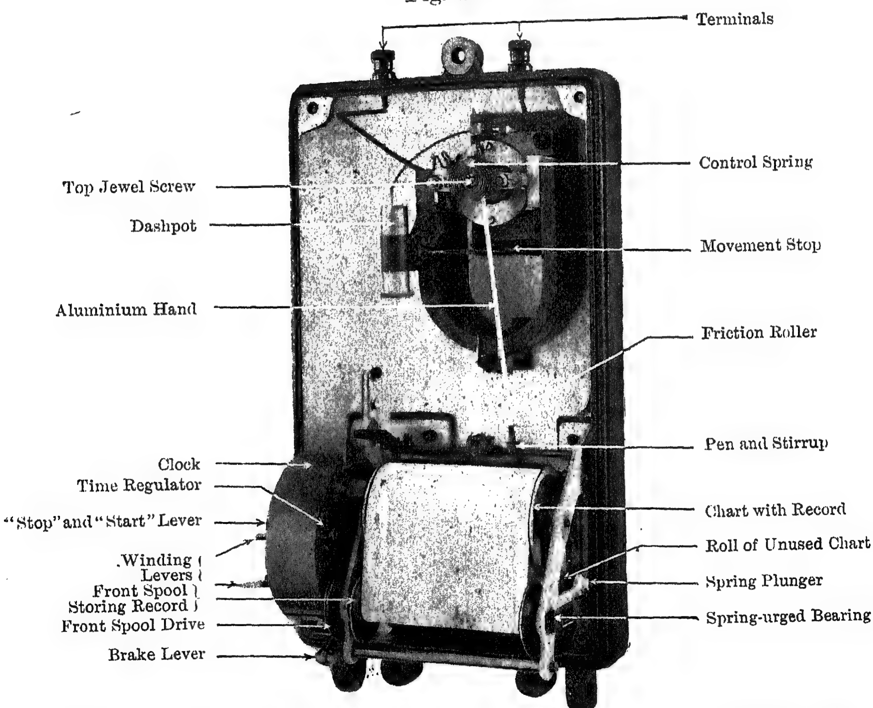


Fig. 23. Evershed's Recording Instruments (Murday's Patent), Moving Coil Pattern. Interior view, illustrating the Continuous or Roll Chart.

expended on such instruments, and some have been produced which are wonderfully good. Fig. 22 gives an outside view and Fig. 23 an interior view of a modern make of recorder.

Portable ammeters and voltmeters are nearly always made for use in the horizontal position. Some of them require levelling.

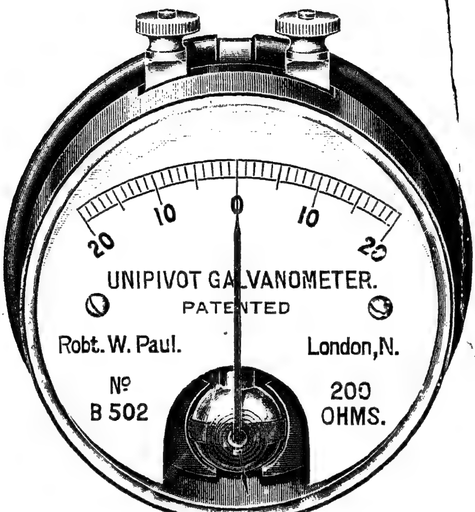


Fig. 24

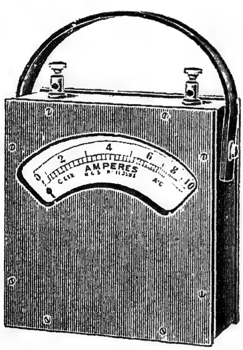


Fig. 25.

Fig. 26.

Instruments of this class are often used when portability is not essential. Ammeters for very accurate work, such as are regularly used in a laboratory, have much finer graduation than switchboard instruments and the pointer usually has a tip consisting

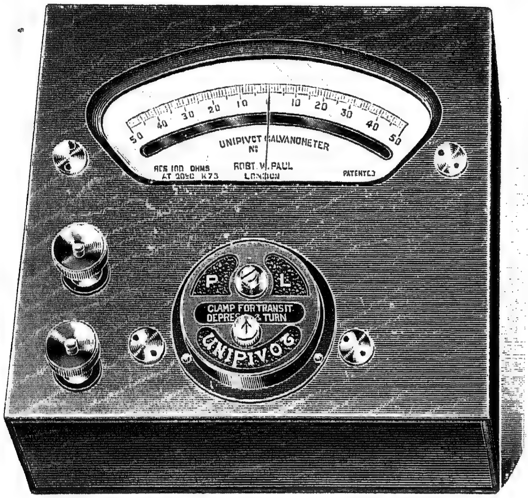


Fig. 27.

of a fine strip on edge to admit of a fine reading. Some have a strip of mirror placed close to the scale (as in Figs. 26, 27, 28); when one is taking readings with instruments so fitted, one looks

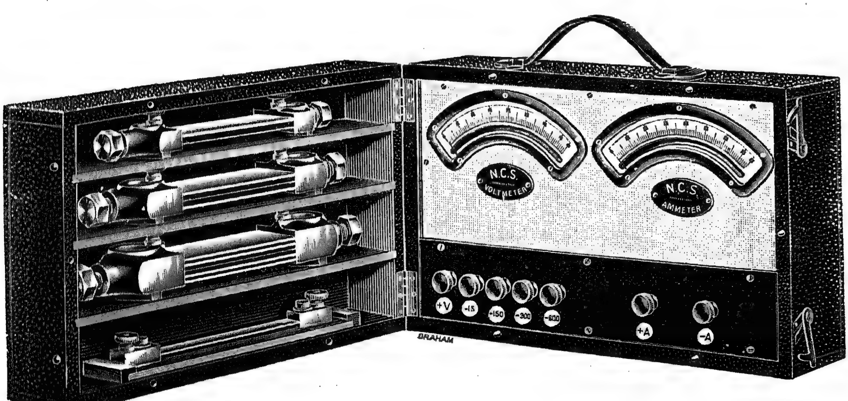


Fig. 28.

at the pointer in such a way that it covers its image in the mirror; in this way it is certain that the pointer is being looked at straight, thus avoiding what are called "parallax" errors. For some purposes it may be necessary to have an instrument with a "central zero" which enables it to show the direction of the current as well as its amount—at the sacrifice of having only half the range. (See Figs. 24 and 27.) Figs. 24 to 29 give illustrations of portable instruments with various arrangements.

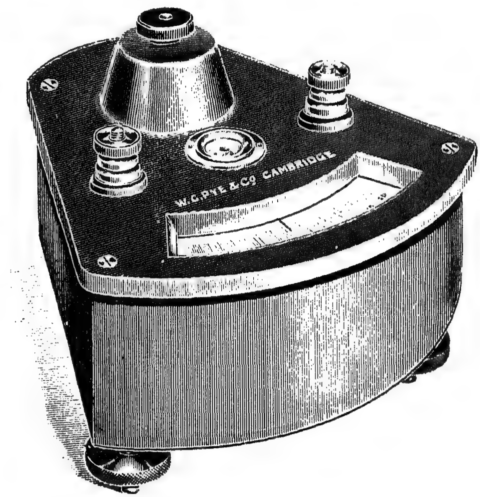


Fig. 29.

Mirror Galvanometers.

Mirror galvanometers are chiefly used to indicate currents of exceedingly small amount—from a microampere downwards. Sensitiveness* is their chief feature and even apart from modifications of internal structure, this is attained in a great degree by the manner in which their indications are read. In place of the pointer of the ordinary ammeter, they have a small mirror attached to the moving part, the current being indicated by means of the

* Sensitiveness does not necessarily imply accuracy. Of two instruments that one is more sensitive which can indicate smaller amounts of the thing measured. Delicacy is so often associated with sensitiveness that "delicate" and "sensitive" are frequently used as if they were synonymous.

mirror's reflections upon a scale—usually placed about a metre away. This is equivalent to the use of a pointer 2 metres long.

The usual plan is to read the deflection from the position on the scale of the reflected image of the shadow of a fine wire in the middle of a "spot" of light proceeding from a fixed source. In order to be able to focus the image, the galvanometer mirror has to be concave and the distance between it and the scale has to be equal to the mirror's radius of curvature: any necessary adjustment of the focus or the position of the zero is easily made

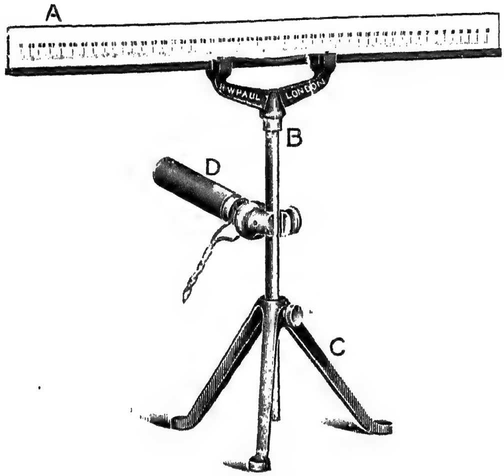


Fig. 30.

by moving the scale to the appropriate position. Fig. 30 illustrates a modern make of lamp and scale fitting; the lantern *D* contains the lamp and fine cross-wire (and lens* for production of a bright "spot"); the provisions for adjustment of scale *A* are obvious.

Fig. 31 shows the appearance of the spot on the scale†.

It is necessary to protect mirror galvanometers from vibrations and tremors such as may be caused by people walking about

* The use of a "split" lens enables the cross-wire to be dispensed with and gives a sharper line on the scale. As a matter of fact, the apparatus illustrated in Fig. 30 is so fitted.

† Generally the spot of light is circular. Fig. 31 illustrates R. W. Paul's latest improvement.

in their neighbourhood. This is usually done by placing the mirror galvanometer on a wall bracket. It is not necessary to make special arrangements for the support of the lamp and scale,

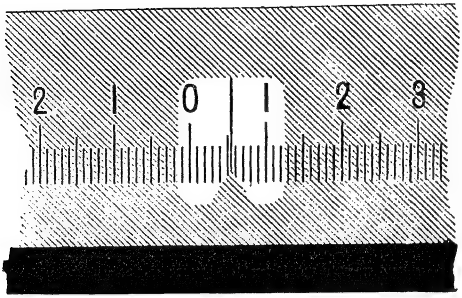


Fig. 31.

but it is often convenient to support them also from the wall carrying the galvanometer. Fig. 32 shows a mirror galvanometer with a complete lamp and scale arrangement entirely wall supported.

At one time it was common to use scales which had to be viewed from the side next the galvanometer*. The use of a

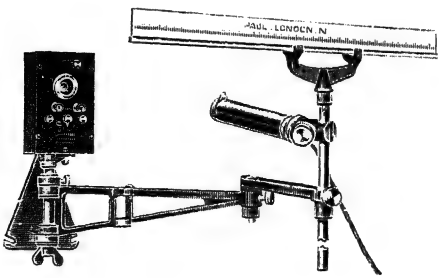


Fig. 32.

"transparent" scale—viewed from the side away from the galvanometer—has the advantage that the head of the observer never obstructs the beam of light, and nowadays opaque scales

* A telescope and scale arrangement has also been used with mirror galvanometers. It is not necessary to go into details respecting this method of reading galvanometer deflections as it is seldom used. It requires the galvanometer to be provided with a *very good plane* mirror.

are hardly ever used. It may also be pointed out that with the small angular deflections used with mirror galvanometers the difference between a circular scale and a straight scale is not a matter of any consequence.

It is frequently necessary to alter the sensitiveness of a mirror galvanometer, and to alter its internal adjustments would be so troublesome that the galvanometer is generally kept at its most sensitive adjustment and change of sensitiveness is effected by the use of a Shunt Box. The sensitiveness of all current measuring instruments can be altered without disturbing their adjustments by the use of so-called "shunts" which "side-track" some of the current, only a part of which then passes through the actual

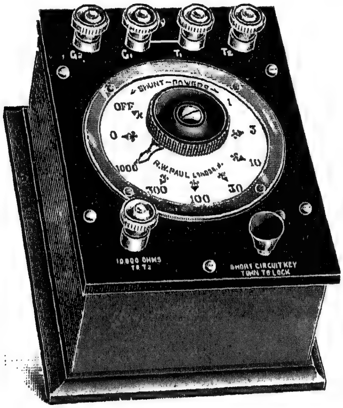


Fig. 33.

instrument. At one time it was usual to make shunt boxes with resistances adjusted to their individual galvanometers so as to reduce the sensitiveness to $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$ of that of the unshunted galvanometer. The Universal Shunt box, invented by Ayrton and Mather, can be used with almost any galvanometer and has practically superseded all the older forms. Fig. 33 illustrates the Universal Shunt box made by Robert W. Paul.

Types of Ammeter.

The following is the classification of current measuring instruments (and corresponding voltmeters) according to the nature of their internal mechanism.

Type	Nature of Mechanism
Moving coil	Current indicated by movement of coil carrying current in field of permanent magnet.
Moving iron (soft iron)	Pointer actuated by forces on piece of soft iron magnetised by current to be measured flowing in a fixed coil.
Hot wire	Pointer actuated by changes of length in wire carrying current.
Dynamometers and current balances	Reading obtained from forces between currents in two sets of coils.
Fixed coil moving magnet	Act on much the same principle as the tangent galvanometer.

Moving Coil Instruments.

The moving coil permanent magnet type of instrument is sometimes also described as the "siphon recorder" type, or as the "D'Arsonval" type, because it works on a principle which was first applied by Lord Kelvin to the siphon recorder and was subsequently applied to mirror galvanometers by D'Arsonval. For the ordinary work of current measurement this kind of instrument is most satisfactory, and the best makes of it may be regarded as falling little short of perfection. Besides having other advantages they are unaffected by any "stray" magnetic fields, whether due to earth currents or other causes. This is obtained by making a small coil of wire carrying the current to be measured—or a definite fraction of it—move between the poles of a permanent magnet producing a field intensity so great that the earth's field and stray fields of ordinary amounts are quite negligible in comparison. The magnitude of the current is indicated by the amount of rotation of the coil which is "controlled" by the elasticity of a metal spring or strip which serves the additional purpose of conducting the current to the coil.

Fig. 34 shows the essentials of an arrangement which may be regarded as typical of this kind of instrument.

Between the poles of a permanent magnet of horse shoe or some other equivalent shape is placed the coil C carrying the

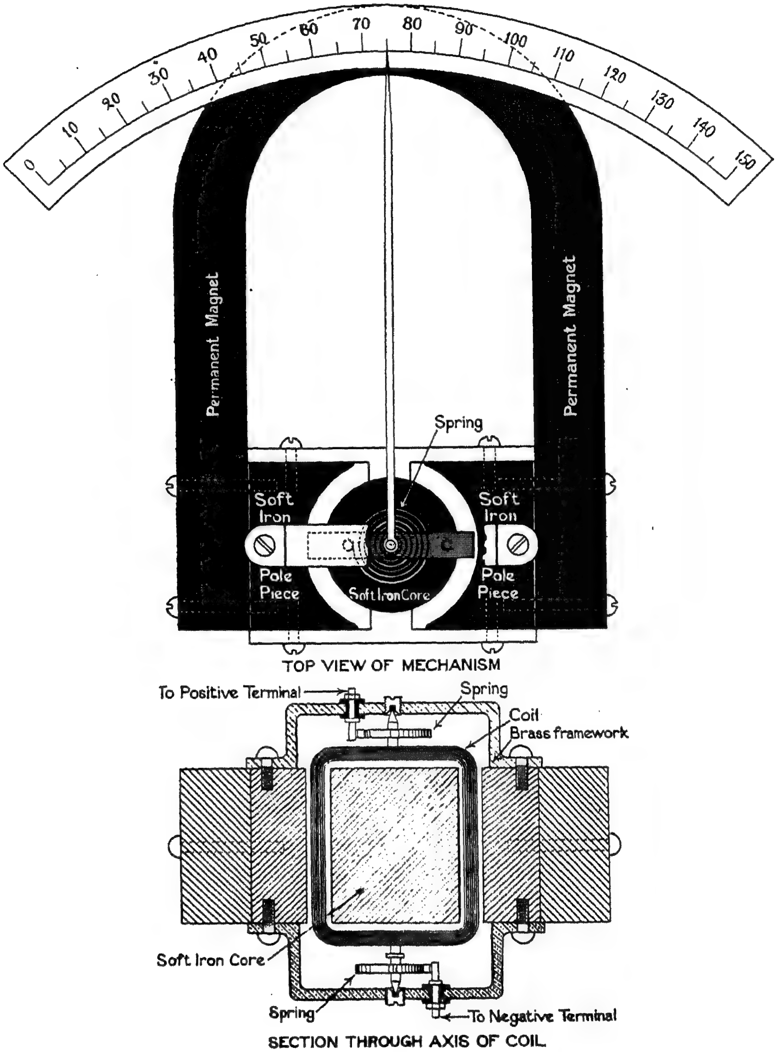


Fig. 34. Moving Coil Instrument.

current to be measured (or a definite fraction of it). The coil is usually wound or supported on a light copper framework

mounted in bearings arranged to be practically frictionless—pivots working in jewelled centres are commonly employed—and controlled by a pair of spiral springs. The current is carried into the coil by means of one of these springs and out by the other, the fixed end of each spring being attached to an insulating support to which the "leads" are connected. A light pointer has one of its ends attached to the coil frame, the other end indicates the reading on a scale. Most instruments of this type have a soft iron core supported inside the coil as shown in Fig. 34.

It has been shown (page 48) that the force acting on a conductor carrying a current in a magnetic field is proportional to the current, and the field intensity; so that the force acting on the moving coil of the type of instrument we are now considering is proportional to the current in it and therefore the turning effort produced is proportional to the current. The controlling turning effort due to the spring is almost precisely proportional to the angle through which the coil turns, and therefore the current will be very approximately proportional to the angle of deflection it produces, if the field intensity is uniform. The soft iron core assists in producing the desired distribution of field intensity, and by means of it and giving suitable shapes to the pole face of the magnet one can arrange the scale to read the current directly with divisions of uniform width*.

The field intensity in the air gap of the magnet is generally about 2000, and so stray magnetic fields of any order of magnitude likely to be met with outside the *immediate* proximity of dynamos and electromagnets are quite negligible in comparison. The earth's field is only about .8 at its greatest and .28 at its least (horizontal component about .17 in this country), and so it and its variations are insignificant.

The only disturbing influence on moving coil instruments is

* Sometimes voltmeters are required only to indicate the fluctuations of voltage in the neighbourhood of a certain normal voltage; to use a moving coil voltmeter with uniform divisions from zero upwards for this purpose would involve a waste of the space occupied by that part of the scale which was not wanted. In a case like this, the unnecessary part of the scale is suppressed, as shown in Figs. 19 and 21, by the use of some device such as a small weight which has to be lifted by the moving coil before the pointer reaches the graduated part of the scale.

change of temperature. To get rid of any change of zero due to this cause the spiral controlling springs are usually wound in opposite directions. Also the material of which they are made is chosen so that its change of elasticity with temperature is negligibly small. Phosphor bronze is one material having this property. The magnetisation of permanent magnets usually varies with the temperature, but magnets are now made in which this effect is extremely small throughout the ordinary range of variation of the temperature of the atmosphere.

The moving parts of the instrument, namely, the coil, pointer, and their attachments, are usually balanced, thus making the instrument give the same reading in any position. This is not essential to the successful working of an ammeter intended for use in a fixed position, but even for such it has the advantage of enabling both horizontal and vertical patterns to use the same form of scale graduation, a thing which would not be possible if gravitational forces were allowed to affect the control of the coil.

When desired the zero of the scale may be made in the middle so that the instrument reads to either side according to the direction in which the current flows through it, but scales are usually arranged to have the zero to the left side as in Fig. 34, in which case the ammeter must be connected in the circuit so as to send the current through it in the proper way to make it read to the right side. In Fig. 34 the coil is shown in the position it would occupy when half the full current it is intended to measure is passing through; this would be the zero position of the coil if the instrument were made to read to either side of a central zero.

To calculate the value of a current from the reading of a moving coil ammeter, one would require to know the field intensity in the air gap of the permanent magnet, the rigidity of the controlling springs, etc.; to obtain these with the requisite accuracy for more than a rough determination would require an elaborate experimental investigation. All this is avoided by simply comparing the readings of the instrument with those given by a "standard" instrument and either marking in the scale divisions to correspond to the true values of the current, or altering the length of the controlling springs, etc. to make the instrument point

to the correct divisions on a previously graduated scale. This process is known as calibrating or standardising the ammeter.

An important requirement of an ammeter (or any pointer instrument) is that the pointer should settle down on the reading indicating the current through it without a great deal of oscillation. When the pointer moves straight to the correct reading, the instrument is said to be "aperiodic." It is not usual to have an ammeter absolutely aperiodic but it is desirable to have it nearly so (except in the case of what are called ballistic instruments, the special use of which cannot be dealt with here), in which case it is said to be "dead beat." A moving coil ammeter is made dead beat by having a piece of good conducting metal (usually copper) moving with the coil; the framework on which the coil is wound or supported usually serves for this purpose. As will be explained later (page 87), when a conducting mass moves in a magnetic field what are called eddy currents are set up; these have the effect of retarding the motion by a force which diminishes as the speed diminishes and ultimately vanishes when the motion ceases. This retarding force therefore only assists in bringing the pointer to rest but does not affect the position in which it does rest; and therefore has no effect on the reading. Ordinary friction would assist in bringing the pointer to rest, but it has to be avoided as it would also affect the position of rest of the pointer and consequently the reading.

As a rule, in moving coil instruments the coil itself is arranged to carry a maximum current of about .1 to .001 ampere, and when the instrument is to be used as an ammeter for measuring larger currents it is provided with a "shunt" through which the bulk of the current passes, a definite fraction only passing through the coil itself. When the instrument is intended for use as a voltmeter, its resistance is increased to a suitable amount by the addition of an extra resistance. In switchboard instruments the shunt or resistance—as the case may be—is generally fitted inside the case of the instrument, but in portable instruments these are frequently made up separately so that by interchanging resistances or shunts they can be conveniently altered for different ranges of measurement. In Fig. 28, there will be seen in the cover of

the instrument, a set of shunts for use with the ammeter. The terminals of sets of resistances for use with the voltmeter are also shown in that Fig.

There are on the market numerous excellent makes* of moving coil instruments, differing in many of their details but conforming broadly to the typical arrangement already described.

In mirror galvanometers of the moving coil or D'Arsonval

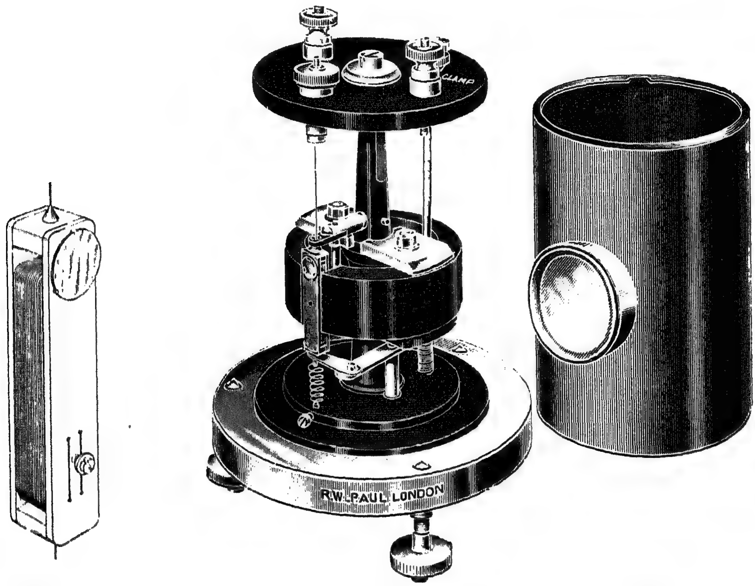


Fig. 35. Paul Reflecting Galvanometer of Moving Coil (Ayrton-Mather) Type.

type, greater sensitiveness is secured by having a single fine strip of phosphor bronze in place of one of the spiral springs and making the other spiral as feeble as possible. The phosphor bronze strip also serves to support the coil, thus dispensing with bearings. These features will be seen from Fig. 35 which illustrates the Paul reflecting galvanometer of the moving coil type.

* Detailed descriptions of various makes of all types will be found in Aspinall Parr's *Electrical Engineering Measuring Instruments*. For a description of a Moving Coil Instrument with scale covering about 300° of the dial, see *Electrician*, Jan. 1913, Vol. 70, page 671.

When it is important to acquire familiarity with constructional details, it is best to examine the actual instruments.

The straight phosphor bronze strip suspension is sometimes used for portable instruments and occasionally even for switchboard instruments with a horizontal scale.

Moving Iron Ammeters and Voltmeters.

The moving iron type owes its existence to the demand for a cheaper instrument than the moving coil, for use under conditions in which accuracy of the order of 1 % is quite sufficient. Hence they are almost entirely confined to switchboard use.

The principle applied in the construction of moving iron ammeters is that of indicating the current either by means of the force set up between a coil carrying it and a piece of soft iron magnetised by it, or by means of the forces set up between more than one piece of soft iron magnetised by the current. These forces are made manifest by the transmission to the pointer of the motion of one piece of iron, the movement taking place against the controlling force, which in these instruments is not, as a rule, supplied by springs but by the weight of the moving parts, generally with the addition of adjustable weights which are fixed finally when the instrument is calibrated. (These two forms of control are distinguished by use of the terms "spring control" and "gravity control.")

The actual forms which such instruments take are naturally very various. Generally they are not made to require the use of shunts. Ammeters have a few turns of stout copper wire or tape on their coil. Voltmeters have many turns of fine wire, and sometimes also additional resistance not wound on the working coil.

In the majority of moving iron instruments the scale divisions are not quite uniform, their proportions depending very much upon the manner in which the pieces of iron are distributed inside the coil of the instrument. In the case of voltmeters these are sometimes deliberately arranged so as to lengthen the divisions near the important part of the scale, that is to give an "open scale" in the desired neighbourhood.

The indications of moving iron instruments in the immediate vicinity of the zero—say under 10 % of the maximum readings—

are practically useless and that part of the scale is frequently left ungraduated. See Figs. 16 and 25.

It will be obvious from what has been said with regard to residual magnetism on page 30 that the magnetisation of a specimen of iron, in a field of given intensity, will be greater for a specimen which has come to that state by having the field intensity *reduced* from a higher value than it will be for a specimen for which the field intensity has reached the same value by being *increased* from a lower value. Therefore the magnetisation of the iron in a moving iron ammeter will be (more or less) greater when the current has been reduced to a certain value from a higher one than when it has been increased to that value from a lower one; that is to say: the readings of the instrument for currents *descending* in value will be higher than the readings at the same currents when the current is *increasing* in value. Most makers are able to reduce the difference between the descending and ascending readings to a matter of 1 %; this is effected by the use of iron of great purity—generally described as soft* iron—because it is in such pure iron that the difference between the descending and ascending values of the magnetisation is least. Information respecting this property of iron and its measurement should be looked for under the head of hysteresis.

We may add that the agreement between the ascending and descending readings is one of the necessary conditions required of a good ammeter of any type. The test as to whether friction is negligible follows the same lines; it is that the reading at any current should be the same whether the pointer reaches the reading by moving up to it or down to it at its last oscillation.

The pointer of a moving iron instrument moves to the same side whatever the direction in which the current is sent through the instrument. This property renders it useless for indicating the direction of a current (not a serious matter for switchboard instruments, but rather a convenience in their case), hence they are never made with a central zero. It may be mentioned here that they can be adapted for use with "alternating" currents

* On this account moving iron instruments often go by the name of soft iron instruments.

(in which the direction of the current is reversed many times a second)*.

Moving iron instruments have been very extensively used in commercial work on account of their cheapness. Recent improvements in methods of manufacture have so reduced the cost of moving coil instruments that moving iron instruments have now very little advantage in this respect. The simple gravity controlled undamped moving iron ammeter is still the cheapest form of ammeter but most people prefer to go to the not very great additional expense of a dead beat instrument. When moving iron instruments are fitted with spring control and made dead beat, there is little difference in cost between them and many good makes of the much superior moving coil type. However, the moving iron type is the one most extensively used for alternating currents.

Any form of instrument can be made dead beat by having attached to the pointer or some part of the moving mechanism a vane which has a dash pot of oil or a confined space of air to move in. The fluid friction set up in such cases is proportional to the speed of the pointer and acts as a brake on its motion while the motion lasts, but ceases to have any effect when the pointer comes to rest and therefore does not affect the reading of the instrument. This method of making instruments dead beat is used in cases when eddy currents cannot be utilised so conveniently. It is applied in the instrument shown in Fig. 39.

Hot Wire Ammeters.

As might be inferred from their name, hot wire ammeters are not electromagnetic in any sense of the word, but measure currents by means of indications derived from the heating effect produced in a wire. When a current is passed through a wire its temperature rises until it loses heat by radiation at the same rate as it is produced by the current. The temperature then attained by the wire depends on the current; its length depends on its temperature. The mechanism of the hot wire ammeter simply serves to

* In the present volume, we shall not be concerned with alternating currents —but only with continuous currents—but it is convenient to make such references in passing.

produce by means of the pointer and scale indications depending on the length of the wire. There are very few makes of this type of instrument and they are principally used for alternating current measurement.

Similar remarks apply to Hot Wire Voltmeters. Mirror instruments of the "hot wire" type have been devised for use as very sensitive alternate current galvanometers.

Calibration.

It is obvious that in order to graduate ammeters and voltmeters correctly we are driven ultimately to use some instrument constructed on lines enabling the current in it to be calculated without difficulty from its reading. Such instruments are called "standard" current measuring instruments. Practically all such standards are constructed to utilise the principle of measuring currents by means of the forces between two circuits carrying the same current (see page 47). If the relative positions of such circuits are kept unaltered during the measurements the current will be proportional to the square root of the force between them. Thus arranged they are capable at once of giving numbers proportional to the currents passed through them. They are thus as good as "calibrated" to begin with. The name "calibration" is given to the process of arranging the scale division of any piece of apparatus to read proportional to the quantity it measures—either that or making a table or curve of the corrections to be applied to the readings of its scale in order to obtain proportional measures. The process of determining the *constant* of the instrument (that is, the multiplier which reduces such proportional numbers to the absolute numerical values) is called "standardisation." Standard current measuring instruments constructed on the principle mentioned only require standardisation to enable them to determine currents in absolute measure; and further this standardisation can be accomplished by noting the reading obtained by sending one current of accurately known value through it. The method of accomplishing this is given on page 74.

Of course *any* ammeter which has been calibrated and standardised and can be depended on to remain "true" to its standardisation, can be used as a standard to test others. Such an ammeter

may be regarded as a "working standard," but it is not in its essence a standard ammeter if its calibration necessarily requires the use of another. Among *essentially* standard current measuring instruments there are two forms working on the principle mentioned in last paragraph, which have come into extensive use. These are the Siemens Dynamometer*, and the current balances of Lord Kelvin. There is one other instrument, working on altogether different lines, which can be used for the calibration of ammeters and voltmeters, and that is the potentiometer. A description of the potentiometer and its uses is given in Chap. VII.

It may be asked what is the necessity for so many various types of ammeter when such standard instruments exist. It is that the use of such standard instruments for the bulk of routine measurements is too slow and laborious and for switchboard work they are quite unsuitable.

Kelvin Current Balances.

Messrs Kelvin, Bottomley and Baird make some ten different forms of standard electric balance (in addition to various special balances), each adapted to particular kinds of measurement. Those intended primarily for current measurement are made in the forms designated as

Centi-ampere	balance,	best part of	range =	.025 to 1 ampere.
Deci-ampere	"	"	"	.25 to 10 amps.
Deka-ampere	"	"	"	5 to 100 amps.
Hekto-ampere	"	"	"	30 to 600 amps.
Kilo-ampere	"	"	"	50 to 1000 amps.

Fig. 36 serves to illustrate the centi-ampere and the deci-ampere balances. There is at each end of the balance a set of three flat coils with their axes in the same vertical line; of these six coils the middle ones (called the movable coils) are fastened to an aluminium framework constituting the "beam" of the balance; the other four coils are fixed, being supported from the base plate. The current to be measured is sent through the six coils in succession in such directions that the forces between each

* A description of the Siemens Dynamometer, which is not now as popular as it used to be, will be found in several text-books. It is described on page 62 of Aspinall Parr's *Electrical Engineering Measuring Instruments.*

pair tend to raise the movable coil on the right and lower the movable coil on the left, and therefore to tilt the beam correspondingly. At the same time, the directions of the current in the movable coils are arranged so that the effect on these of the

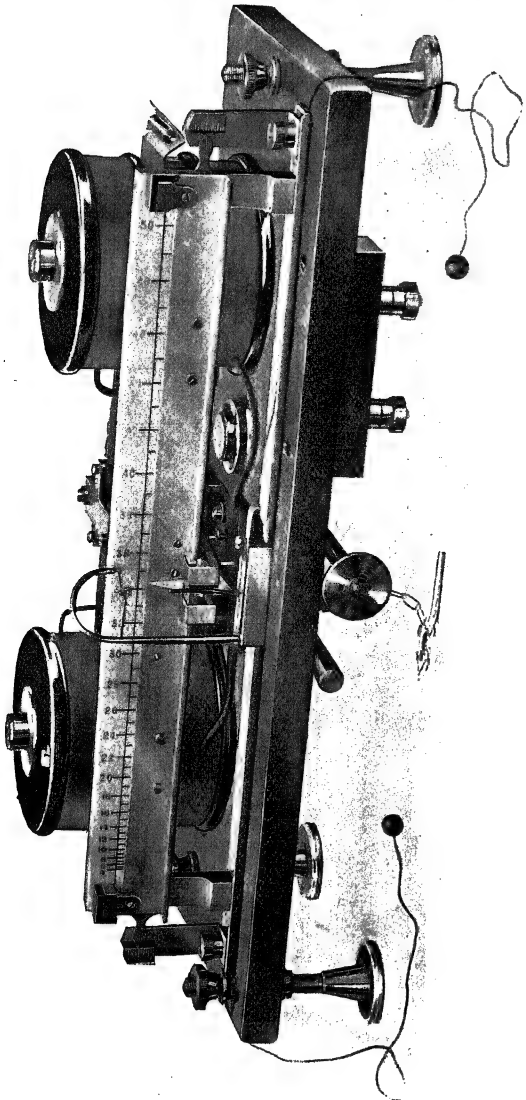


Fig. 36. Kelvin Centi-Ampere Balance.

earth's magnetic field is neutralised; in fact, the balance is not disturbed by "stray" fields so long as these are such as to have the same vertical component at each of the movable coils, a precaution easily secured in practice by keeping magnetic matter at a moderate distance.

Instead of supporting the beam of the balance by the usual knife-edge arrangement, it is suspended from two sets of ligaments of fine copper wire which serve the double purpose of providing a frictionless fulcrum for the beam and of conducting the current to and from the movable coils. A uniform scale, called the movable scale, is graduated on the front trunnion of the beam of the balance, and the tilting force is measured by means of the distance along which a sliding weight has to be moved in order to restore equilibrium. The equilibrium position of the beam is observed by means of the pointer at each end of the trunnion. In the equilibrium position the movable coils are not quite midway between the fixed coils but about .2 % nearer the repelling coils, in order to give stability. The balance is provided with a glass case to prevent disturbance due to air currents, and the adjustment of the weight during the process of taking a reading is made from the outside of the case by means of silk threads running out through holes in the case from a slider which is ingeniously devised so as to swing free from the sliding weight when the threads are slackened.

The current is proportional to the square root of the reading obtained from the movable scale, and the weights provided with each balance are arranged so that twice the square root of this reading is some simple multiple of the actual current. A table of doubled square roots is supplied with the balance to save arithmetical calculation. The balance itself is also supplied with a fixed scale placed immediately behind the movable scale; this fixed scale is graduated so as to show the double square root of the movable scale readings, and can be used when rapidity of working is of more importance than great accuracy. Four sliding weights are supplied with each balance so as to extend its range for accurate work. To save trouble in adjusting the counterpoise of the beam before commencing measurements, for each sliding weight there is supplied a corresponding counterpoise weight to

be placed in a small V-shaped pan provided for the purpose at the extreme right of the beam. A vane, worked by a handle which will be seen projecting below the front of the base plate, in Fig. 36, is provided for the delicate finishing adjustment of the counterpoise of the beam.

After such a balance is constructed the only thing to be done in order to make it available for absolute measurements of current is to adjust the sliding weights so as to make its reading with any current such that the value of the current calculated from the reading agrees with the true value of that current. In fact only one of the sliding weights need to be determined in that manner as the weight of the others can be obtained from it by proportion. To carry out this adjustment one requires to use a current the absolute value of which can be determined by some outside means. Any method based upon calculation of the forces between the coils from their dimensions is out of the question, not merely on account of mathematical difficulties, but because of the practical difficulties of obtaining the dimensions of the coils with the requisite accuracy.

Kelvin balances are made not only for use as standards for the measurement of current, but also for the measurement of electromotive force and the electrical measurement of power. The centi-ampere balance can obviously be used in conjunction with a known high resistance for the absolute determination of electromotive forces. Some balances are adapted for the measurement of the power supplied to a circuit. We may add that most of the Kelvin balances are equally adapted for use with alternating currents.

Standardisation.

However much we may in practice standardise current measuring instruments by an already standardised instrument, the means of determining the absolute value of some one current in some independent way is an ultimate necessity. The absolute value of a current may be measured—as indicated on page 47—by using a "current weigher" in which the force between two coils (designed to admit of accurate measurement of all dimensions) carrying the current is determined directly by means of weights, but such an

experiment is too elaborate for general use, and what is done in actual fact is to use such an apparatus to determine the amount of silver deposited per ampere per second from a solution of silver nitrate under certain specified conditions. Various experimenters have made careful and elaborate determinations of the deposit of silver per ampere per second which seems to be .001 118 gramme. (The best recent determinations only differ in the figures following the 8.) The international ampere is now defined as the current which yields a deposit of silver (under certain specified conditions) of .001 118 00 gramme per second. We have not given the usual definition of the ampere which need not concern us, as the above is the definition applicable for all practical purposes*.

The standardisation of current measuring instruments by means of the electrolysis of silver nitrate is, nevertheless, a matter involving some trouble, and in several cases the electrolysis of copper sulphate has been used instead†. Even that, however, is not sufficiently expeditious and simple, and therefore another means has been devised, viz. the Potentiometer method described in Chap VII. (page 166), in which a standard cell and standard resistance are used. The E.M.F. of the standard cell is determined by means of a standard resistance and either the electrolysis of silver nitrate or a current weigher. (The potentiometer method can be applied to calibrate and standardise simultaneously.)

It is not often necessary to calibrate or standardise a mirror galvanometer but when this is required it is done by means of a cell of known E.M.F. and known resistances.

* See the report of the "Conference on Electrical Units and Standards," for which invitations were issued by the British Government, held in October, 1908, in the *Electrician*, Vol. 62, page 101, Oct. 1908.

† A research by Prof. T. Gray (see *Phil. Mag.* Oct. 1886) has discovered the conditions for success in the use of copper sulphate electrolysis for the purpose we are considering. For full details the reader is referred to the account of these experiments in A. Gray's *Absolute Measurements in Electricity and Magnetism*, Vol. 2, Part II, pp. 417 *et seq.* It suffices to state here that using a solution of pure copper sulphate crystals in distilled water slightly acidulated with a drop or two of sulphuric acid and copper plates made chemically clean by scrubbing with silver sand, the deposit of copper will be very approximately at the rate of .000 329 4 gramme per ampere per second, if the current used is about $\frac{1}{5}$ ampere for each square inch of surface of the copper plate receiving the deposit.

See also a paper read before the Physical Society in London on 12 June, 1914, by A. G. Shrimpton on "The Atomic Weight of Copper by Electrolysis."

Moving Coil Dynamometer Instruments.

In addition to moving coil instruments employing a permanent magnet, there is another class of moving coil instruments in which a set of fixed coils are substituted for the magnet. These are called dynamometer instruments because they act on the same principle as the Siemen's Dynamometer, viz. the forces between currents in two sets of coils—although their indications are not read in the same manner as in the original dynamometer of Siemens.

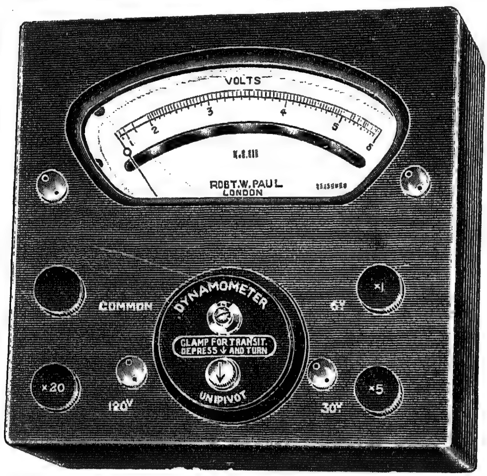


Fig. 37. Paul Unipivot Dynamometer Instrument.

The nature of their internal mechanism will be readily understood from the fact that their only difference from ordinary moving coil instruments consists in having their magnetic field provided by the current in a set of fixed coils grouped round the moving coil instead of a permanent magnet and the consequential modification of construction. Fig. 38 shows the arrangement of the coils in Paul's Unipivot Moving Coil Dynamometer instruments.

In ammeters and voltmeters of this type the same current passes through the fixed and moving coils and the force acting on the moving coil is proportional to the square of the current so that the scale divisions are not uniform; see Fig. 37. A shunt

or a series resistance is used in conjunction with the instrument according as it is to be used as an ammeter or a voltmeter.

The chief reason for manufacturing instruments of this type is that they can be used for either continuous or alternating currents. This type is also very adaptable for use as a wattmeter, that is, for the electrical measurement of power.

It may be mentioned here that the power supply to an electric circuit is proportional to the product of the electromotive force and the current. When the electromotive force is stated in volts and the current in amperes, their product measures the power in watts, the watt being the electrical unit of power. (One horse-

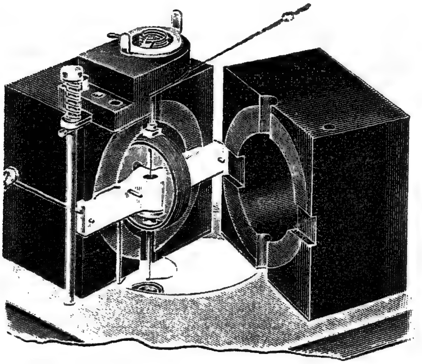


Fig. 38. Fixed and Moving Coils of Paul Dynamometer Instrument.

power is equivalent to 746 watts.) If the current in a circuit is sent through one of the sets of coils—say the fixed coils—of a dynamometer instrument and the electromotive force is applied to the other—say the moving coil—through a high resistance the force acting on the moving coil will be proportional to the product of the currents in the two sets of coils and therefore to the product of current and electromotive force, so that the deflection of the instrument will indicate the power supplied to the circuit and the instrument can be graduated to read the power in watts or kilowatts or even in horse-power.

The same principle is applied in the Watt-Balances of Lord Kelvin.

Electrostatic Voltmeters.

It has already been pointed out on page 50 that for every type of ammeter there is a corresponding type of voltmeter, but there is one type of voltmeter in addition to all these, viz. the electrostatic voltmeter.

The electrostatic voltmeter consists essentially of two sets of vanes insulated from each other. One of these sets of vanes is fixed and connected to one terminal of the instrument; the other

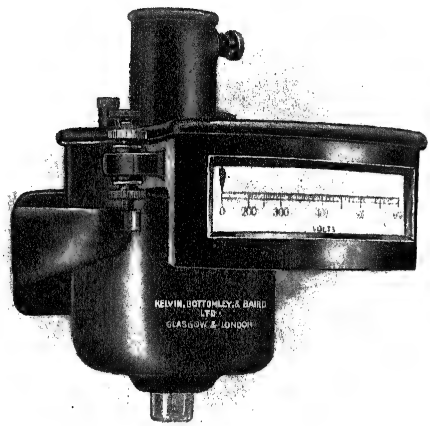


Fig. 39. Kelvin Multicellular Electrostatic Voltmeter.

set of vanes is suspended by a metal fibre which also supplies an electrical connection leading ultimately to the other terminal of the instrument. When an electromotive force or difference of potential is applied to the terminals of the instrument, one set of vanes become positively electrified and the other set of vanes become negatively electrified, consequently they attract each other, and the instrument is so constructed as to make this attraction pull the movable vanes into the spaces between the fixed vanes by rotation about the axis of suspension. The voltage of the difference of potential is indicated on a scale by a pointer attached to the set of movable vanes.

This type of voltmeter requires calibration to enable the scale to be marked off directly in volts. To check the zero of this instrument it is necessary to connect its terminals by a conductor as this is the only way of ensuring the removal of any charge of electricity which might produce a difference of potential between the two sets of vanes. A switch contact for this purpose is generally provided on the instrument. The sensitiveness—and consequently the range of the instrument—is varied by alteration of the number of vanes or the stiffness of the suspension.

Fig. 40. Ayrton-Mather Electrostatic Voltmeter.

Figs. 39 and 40 illustrate two different makes of electrostatic voltmeters.

The Electromagnet.

Another piece of apparatus the principle of which will be readily understood from the matter contained in this chapter is the electromagnet. This apparatus is simply an appliance for producing fields of great field intensity from the magnetic effects of a current of electricity. It consists essentially of a set (generally

two) of coils of insulated copper wire inside which are cores of very soft iron placed upon a yoke also of soft iron, which generally serves also as the base of the apparatus.

The iron increases and concentrates the magnetic force of the coils themselves through the action of the magnetism induced. This effect is also enhanced by the use of suitable pole pieces.

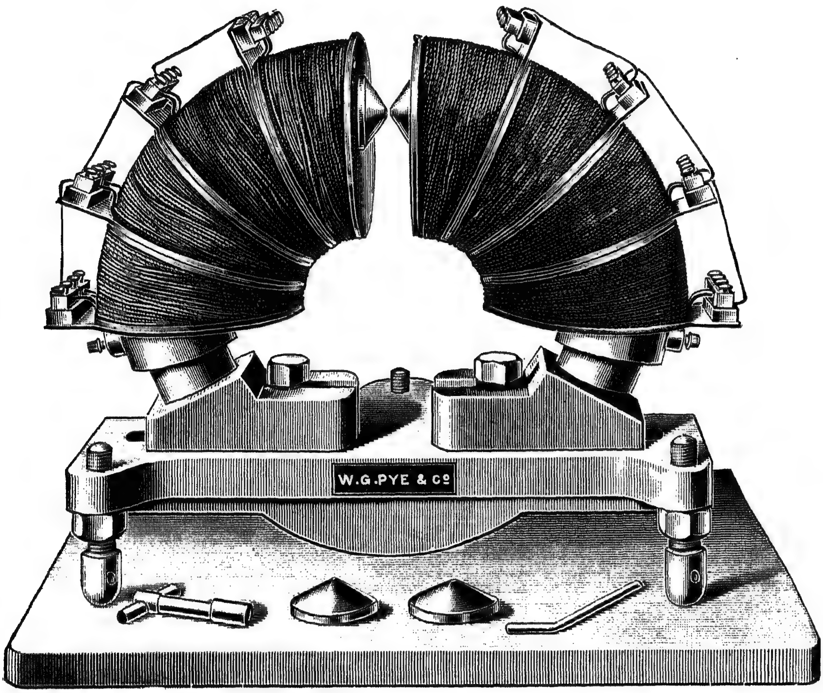


Fig. 41. Du Bois Semi-circular Electromagnet.

To obtain magnetic fields of exceptionally great intensity it is necessary to employ pole pieces with a comparatively small tip and to have these placed fairly close together.

Many forms of electromagnets have been made but the form known as the Du Bois Semi-circular Electromagnet (designed by Dr Henri Du Bois) is the modern standard pattern. This electromagnet, which is illustrated in Fig. 41, is arranged for the convenient performance of a large variety of measurements, details of which

are beyond the scope of the present work. Electromagnets of this design can be made to produce field intensities up to between 30 000 and 50 000 over an area sufficient for most experiments.

Fig. 42 illustrates the straight form of electromagnet which was at one time in almost universal use. This pattern is quite useful for work with field intensities up to 5000 or even more, but the fact that the magnetic force due to the current in the coils is

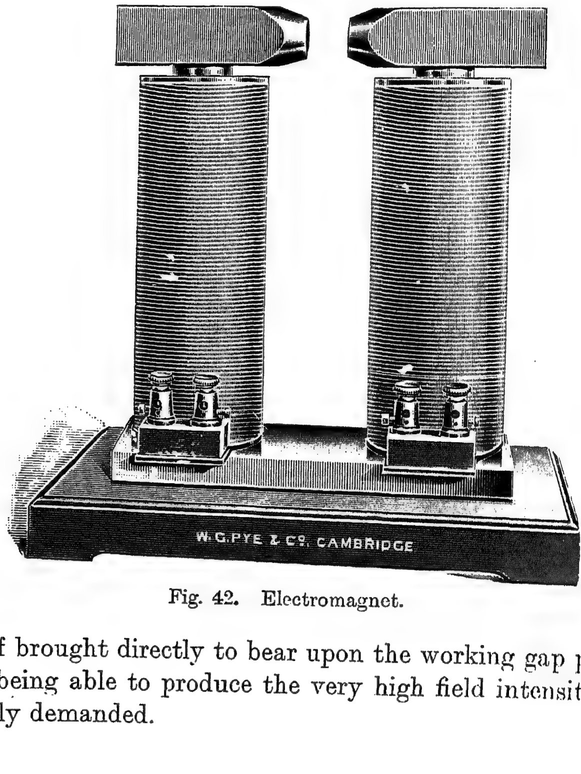


Fig. 42. Electromagnet.

not itself brought directly to bear upon the working gap prevents it from being able to produce the very high field intensities now frequently demanded.

MISCELLANEOUS QUESTIONS ON CHAPTER IV

40. Sketch the form and distribution of the lines of magnetic force in the field surrounding a long straight conductor which carries a current. Give a second sketch showing similarly the lines of force in the field of two parallel straight conductors carrying currents flowing in the same direction. (C. and G. 1910.)

41. Describe the construction of some form of suspended coil galvanometer. What advantage does such a galvanometer possess over the Thomson mirror type? (C. and G. 1913.)

42. Describe a tangent galvanometer and explain the principle on which it acts. What are the relative strengths of three currents which are observed to produce deflections of 30°, 45° and 60° on the same tangent galvanometer ($\sqrt{3} = 1.73$)? (C. and G. 1912.)

43. State the essential difference between moving coil, moving iron and hot wire measuring instruments and the advantages and disadvantages of each on A.C. and D.C. circuits for steady and fluctuating loads respectively. (C. and G. 1913.)

44. Mention the principles on which the action of different types of voltmeters is based, and state the conditions for which each type is most suitable. (C. and G. 1912.)

45. What are the means employed to increase the range of instruments for measuring voltage and current? (C. and G. 1913.)

46. Describe the construction of an ammeter and a voltmeter. How are they used, and what is the essential difference between them? (C. and G. 1911.)

47. Sketch and describe some form of galvanometer. For what purpose may this instrument be employed? (C. and G. 1913.)

48. Describe, with sketches, some form of moving coil ammeter, and explain (*a*) how a uniformly divided scale is obtained, (*b*) how the instrument would be arranged to measure a very large current. (C. and G. 1911.)

49. A continuous current voltmeter has a resistance of 1000 ohms and a scale divided into 150 equal parts. A deflection of 100 divisions of the scale is obtained with a difference of potential of 1 volt between the terminals. Explain how this instrument can be used for measuring up to 150 volts, and give a diagram of connections. (C. and G. 1913.)

CHAPTER V

ELECTROMOTIVE FORCE

"Induced" Currents.

Currents of electricity can be produced by the motion of a conducting circuit in a magnetic field, or by the motion of a magnetic field in the neighbourhood of a conducting circuit.

This can be shown experimentally by means of the apparatus illustrated in Fig. 43. Let C be a coil of wire connected up to a

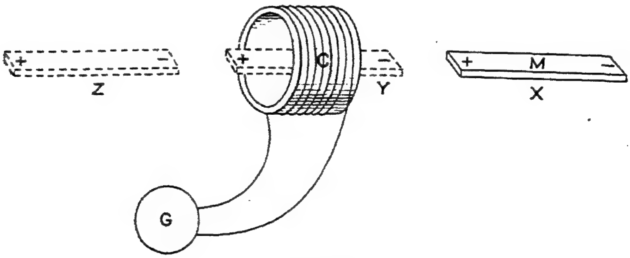


Fig. 43.

galvanometer G: then if a bar magnet M is brought from any position some distance away—such as that shown at X—to the position indicated by Y, a deflection will take place in the galvanometer, indicating the passage of a current for the time being. If the magnet is moved to the position indicated by Z another deflection will be observed indicating a current in the opposite direction from before. If the motion of the magnet be reversed in either of these cases or the same motions be made with the magnet having its poles reversed, deflections will be again observed indicating currents in the opposite directions respectively from

the previous cases. This shows that while the motion was taking place an electromotive force existed in the circuit.

We may picture to ourselves what has been happening in these cases by imagining the lines of force representing the magnetic field of the magnet to be moving along with it and in doing so to cut through the wires of the coil in their passage. Every time a line of force cuts through one of the turns of wire in the coil, a "cut" is said to take place. All phenomena such as the above can be explained by assuming that an electromotive force is produced in the wire which is at every instant proportional to the rate at which "cuts" take place at that instant. (This holds for all lines of induction. See page 38.)

The apparatus shown in Fig. 44 can be used to show experimentally the electromotive force in a circuit produced by cuts made by lines of force due to a current. Let C be a coil of wire connected up to galvanometer G and M be another coil of wire

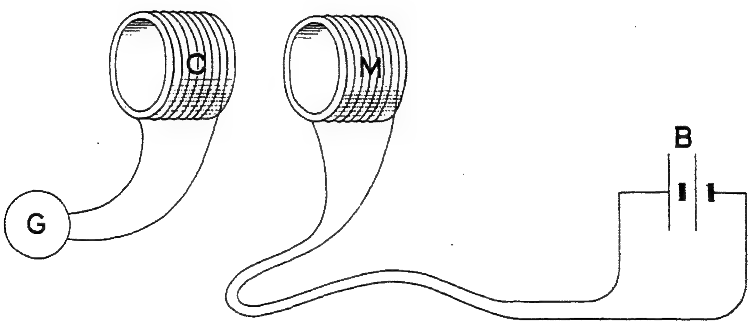


Fig. 44.

carrying a current produced by the battery of cells B; then if the coil M is moved towards C, a deflection will take place in the galvanometer. Moving the coil M away from C will also produce a deflection, but in the opposite direction. Breaking the current in the coil M will also produce a deflection; making the current will produce an opposite deflection. Such experiments may be made in almost endless variety*.

* See Faraday's original papers.

Measurement of "Induced" E.M.F.

The relation between the direction of the E.M.F. produced in a conductor and the direction of its motion relatively to the magnetic field is shown in Fig. 45. A convenient way of remembering this relation is the following. The lines of force proceed from positive magnetism which is also called north magnetism. Let the observer imagine a capital N to be seen in the direction from which the lines of force are coming with its outside strokes parallel to the conductor as shown in Fig. 46. The direction of the E.M.F. induced by the motion of the conductor

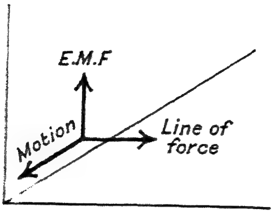


Fig. 45.

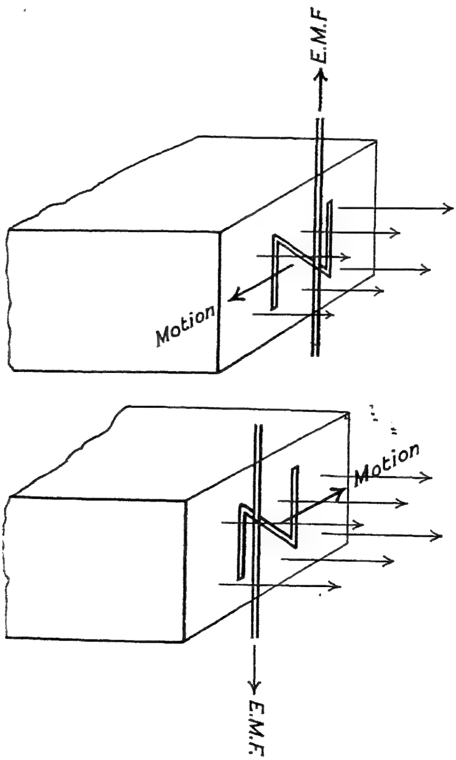


Fig. 46.

will be given by the direction of travel of the conductor's intersection with the diagonal stroke of the *N*.

To determine the amount of an E.M.F. induced in the above manner in any circuit at any instant, it is only necessary to take a very short interval of time including that instant, find the number of cuts which produce an E.M.F. in one direction round the circuit, and the number of cuts producing an E.M.F. in an opposite direction round the circuit, and divide the difference between these by the interval of time. The direction of the resultant E.M.F. is that of the E.M.F. due to the cuts which are greater in number. The C.G.S. electromagnetic unit of E.M.F. is that produced in a conductor which has one line of force cutting it per second. The volt is the E.M.F. in a conductor which makes 10^8 (one hundred million) effective cuts per second.

The above indicates the method applied to the calculation of the E.M.F. produced by a dynamo (or to the design of a dynamo to produce a given E.M.F.). The dynamo is a machine having an arrangement of conductors made to revolve inside a set of electromagnets, or *vice versa*.

It is, however, difficult to devise an apparatus working on the principles given above for the accurate measurement of electromotive forces, and in actual practice the measurement of electromotive forces is made to depend on the measurement of current and resistance. However, they are applied in the determination of the resistance which is to represent the ohm.

Determination of the Ohm.

The method of determining the ohmic value of a resistance —so as to be able to measure other resistances by comparison— may be here indicated. The method now generally used is that originally devised by Lorenz *. The essentials are represented diagrammatically in Fig. 47. Current from a battery *B* is sent through a coil *C* (constructed so as to have all its dimensions

* Particulars of various determinations and illustrations of actual apparatus —including the latest form at the National Physical Laboratory—will be found in the report of the fourth Kelvin Lecture delivered by Dr Glazebrook on "The Ohm, the Ampere and the Volt: a memory of fifty years, 1862–1912" in the *Journal of the Institution of Electrical Engineers*, Feb. 1913, Vol. 50, pages 560 *et seq.*

capable of accurate measurement) and the resistance R whose amount is to be fixed. Inside C is a disc D which is driven so as to produce an induced E.M.F., the amount of which can be calculated from the speed of rotation (which is measured with great accuracy by special methods) and the dimensions, etc., of the coil and disc. Everything is adjusted so that the E.M.F. produced by the disc is equal and opposite to the difference of potential between the terminals of the resistance R due to the main current through it, this adjustment being checked by observing no deflection in the very sensitive galvanometer G.

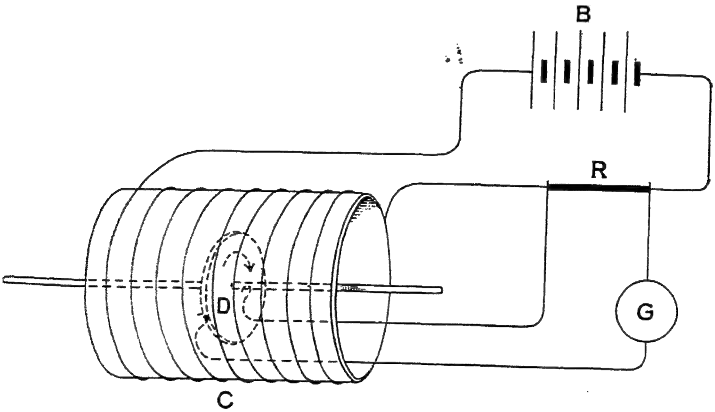


Fig. 47.

In calculating the resistance of R, the main current cancels out and the number of ohms in R is found in terms of the speed of D and other quantities which can be obtained by measurement. From R, other resistances can be determined, and for purposes of comparing results they are stated in terms of the specific resistance of pure mercury at the temperature of zero centigrade.

On the basis of the best recent experiments, the International Ohm is defined as the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grammes in mass, of a constant cross-sectional area and of a length of 106.300 centimetres. (See *Electrician*, Oct. 1908, vol. 62, page 104.)

Lenz' Law.

When a conducting circuit moving in a magnetic field has a current produced in it (by the E.M.F. which the motion gives rise to) the magnetic force produced by the current is always such as to oppose the motion which gives rise to it. This was discovered by Lenz and is known as Lenz' Law. It is a particular case of a general law of nature, viz. that whenever any change—in the magnitude of a current or position of a conductor, etc.—produces any effect, the resulting action of such an effect is to oppose the change.

Eddy Currents.

When a piece of conducting material is moving in a magnetic field the cuts which the various parts of it make give rise to electromotive forces which produce currents which circulate in the material itself. Such currents are called eddy currents. These eddy currents produce magnetic forces which tend to resist the motion producing them (see Lenz' Law). The action of the copper frames or tubes attached to the coil of moving coil ammeters, to make them dead beat, is thus explained.

The energy of eddy currents is taken from the energy of the motion which gives rise to them and becomes dissipated into heat. On this account elaborate precautions are taken in the construction of dynamos and motors to reduce the loss of energy caused by eddy currents to a reasonably small amount.

The Dynamo.

The principles mentioned above find their most extensive practical applications in the construction of dynamos which are machines used, either as generators for the production of electricity by the relative motion of sets of copper conductors and magnetic fields, or as motors for the production of mechanical power from the magnetic forces produced by currents of electricity. Dynamos are naturally divided into two great classes—continuous current dynamos and alternating current dynamos, and there are several types in each of these great divisions.

Alternating currents are those in which the direction of the current is reversed with a regular periodicity and in modern practice the number of complete cycles or alternations is generally something between 20 and 60 per second. Occasionally an alternating current is "rectified" or has the pulsations of current made to have the same direction, in which case it is described as

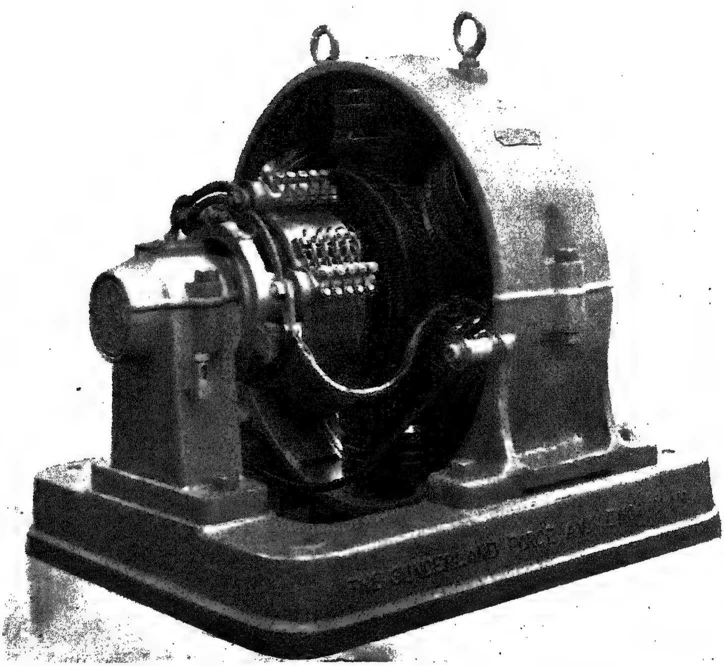


Fig. 48. A Continuous Current Dynamo.

a "uni-directional" current, to distinguish it from continuous currents which have a more or less regular flow in the same direction throughout comparatively long periods.

Continuous Current Generators.

Continuous current generators usually consist of a stationary field magnet with its yoke on the outside of the machine and 2 or more pairs of poles pointing inwards—dynamos with 2 poles

(1 pair) are not common in these days—and an armature (carrying the conductors in longitudinal slots and a commutator at one end) which revolves inside the field magnet. The current is collected by stationary rows of brushes arranged round the commutator on which they press lightly.

The various parts of such a dynamo will be seen in Fig. 48 which gives an illustration of a complete dynamo, Fig. 49 which shows an armature separately and Fig. 50 which shows longitudinal and transverse sectional views.

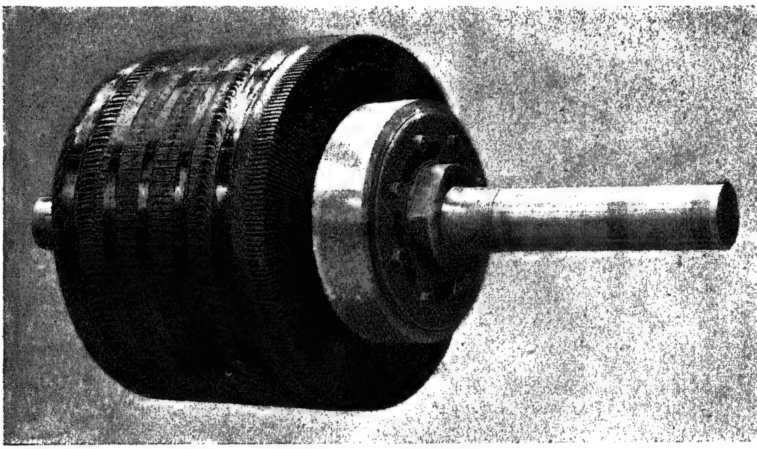


Fig. 49. An Armature of a Continuous Current Dynamo.

It will be seen from Fig. 50 that the armature contains an iron core. This is provided to " draw " the lines of induction leaving the poles down into the body of the armature and to reduce the leakage of such lines, many of which would otherwise escape from being cut by the armature conductors. The arrangement of the lines of induction in the magnetic system of the dynamo will be understood from the diagram shown in Fig. 51. (Only a few of the lines can be shown in the Fig.; in an actual dynamo there would be about 8000 to 10 000 lines for every square centimetre of surface on the pole face.)

The magnetic force producing the lines referred to is provided by current in the coils fixed on the poles of the field magnet.

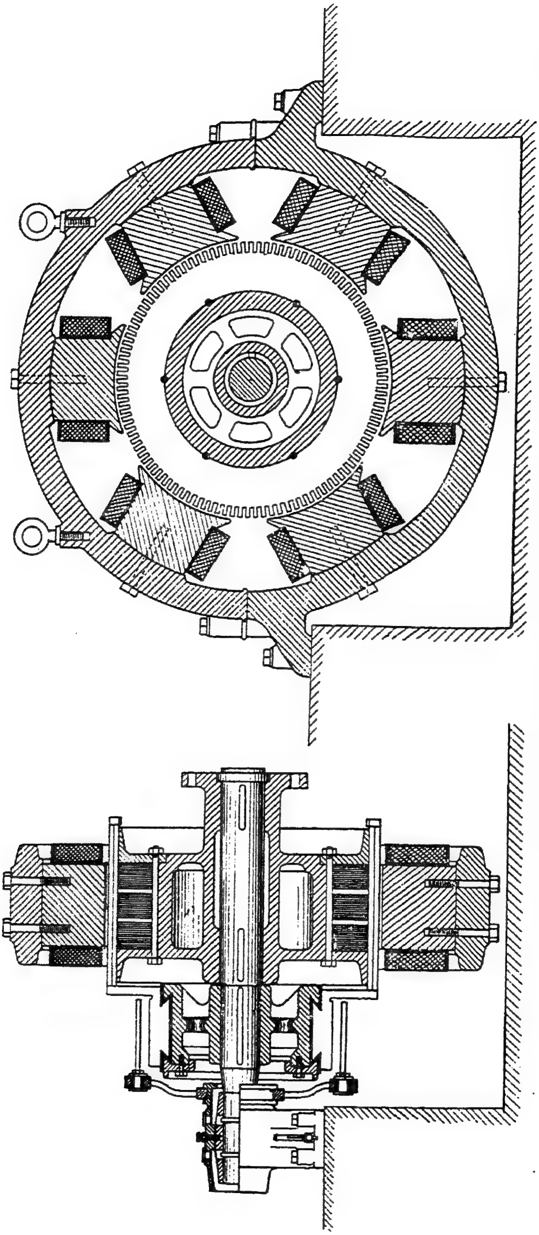


Fig. 50. Sectional Views of 6 Pole Continuous Current Dynamo.

It is scarcely necessary to mention—after what has been said on page 41—that the magnetic force produced by each field coil is proportional to the current in the coil; but it should be explained that large magnetic forces do not *necessarily* involve the use of large currents in the field coils. If the number of turns in a field coil is increased, it is equivalent to a proportionate increase in the

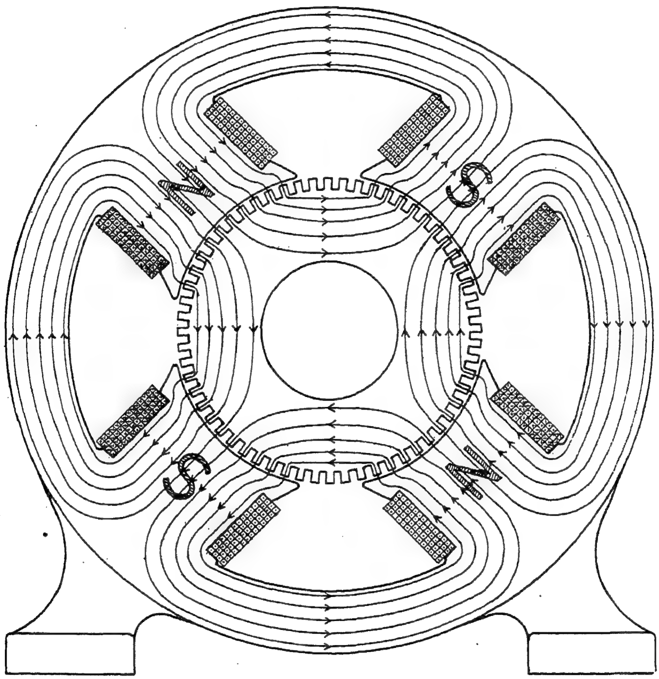


Fig. 51.

amount of electricity going round the coil per second, and therefore produces a proportionate increase in the magnetic force. The magnetic force of a coil is proportional to the current in the coil and to the number of turns, and therefore to the product of these which is generally expressed in ampere-turns.

It may be inferred from Fig. 51 that when the armature revolves, the armature conductors cut lines giving rise to electromotive forces. The conductors under each pole of the field

magnet have electromotive forces all in the same direction; the direction changes when the conductors come under the next pole, and so on. The winding of the armature is devised so that these are combined to produce currents flowing towards alternate rows of brushes from the other rows of brushes.

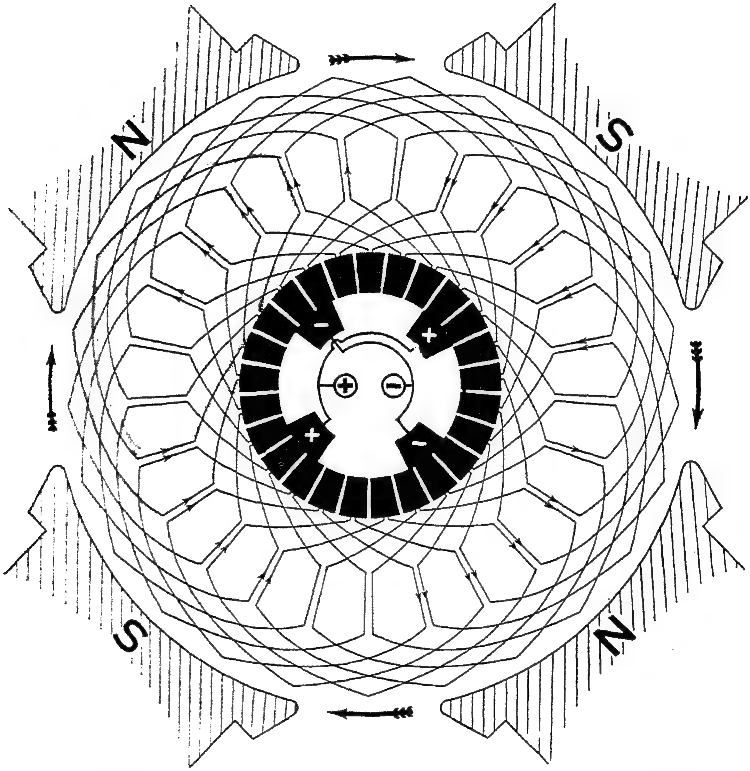


Fig. 52. Diagram of 4 Pole Lap Wound (4 circuit) Continuous Current Generator.

It is not easy to make a flat diagram which will give a view of the whole of the parts of the entire machine in their relative positions, but if we imagine the armature conductors to be opened up in a sort of umbrella fashion we get the arrangement shown diagrammatically in Fig. 52 which shows the manner in which the armature conductors are connected and the directions of the

currents in the various parts thereof*. Fig. 52 also shows the necessity for the so-called commutator which is simply provided

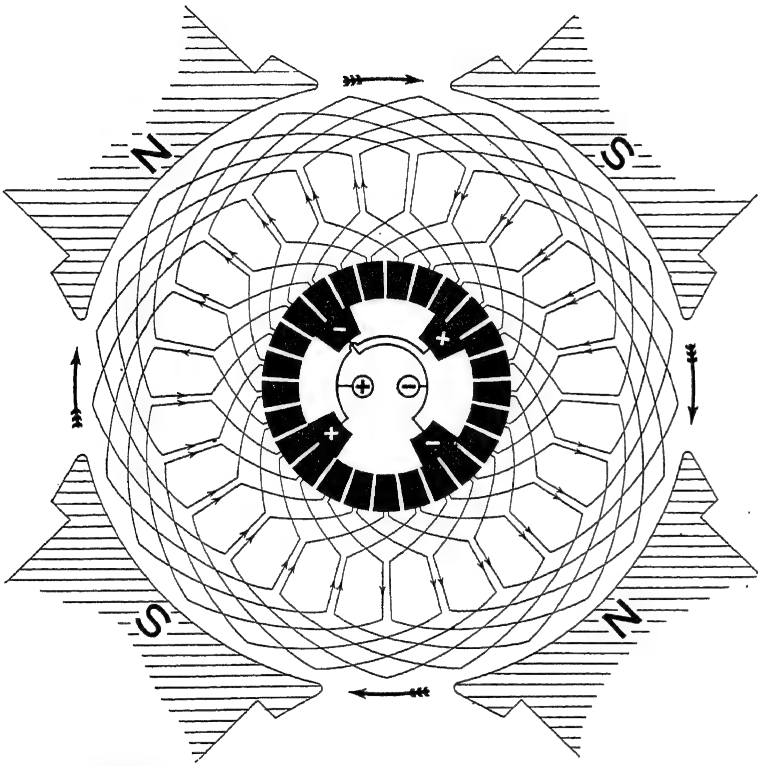


Fig. 53. Diagram of 4 Pole Double Lap Wound (8 circuit) Continuous Current Generator.

* In Figs. 52, 53, 54, arrows are omitted from the conductors undergoing commutation, that is the conductors in which, for the time being, the direction of the current is undergoing reversal—as explained below, page 98.

For the sake of clearness these diagrams are represented with much fewer conductors than would be used in any actual dynamo; consequently the proportion of conductors in which current reversal is taking place is unduly large in the diagrams even although the number of commutator segments touching one brush at a time is on the small side.

The parts of the conductors which would lie vertically together in the same slot are drawn closer together in these diagrams. The bold arrows in the gaps between the poles indicate the direction of rotation for which the diagrams are drawn.

to enable the fixed brushes to change their point of contact with the revolving armature winding, so as always to keep it at the appropriate place.

The style of armature winding shown in Fig. 52 is that most commonly used. It is called a lap winding. Other styles are

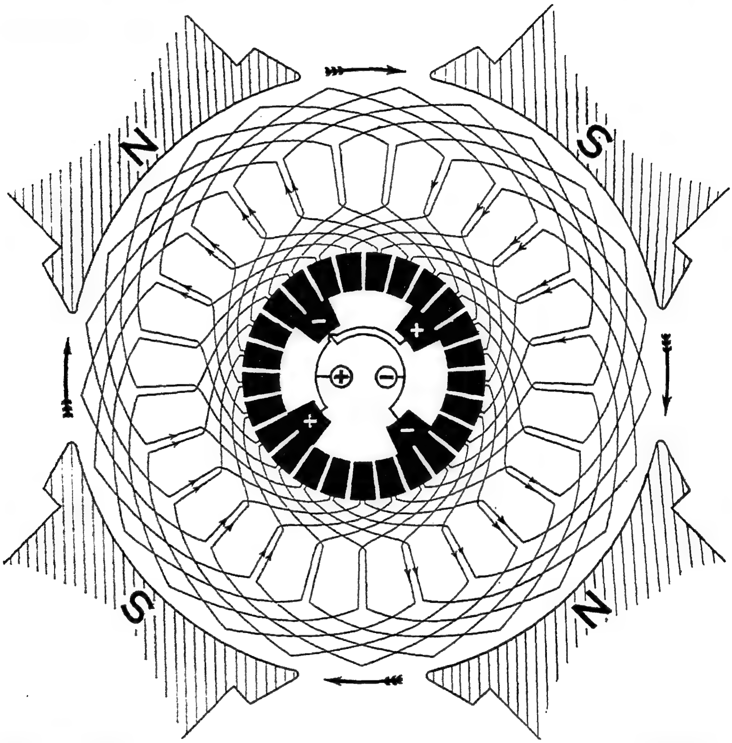


Fig. 54. Diagram of 4 Pole Wave Wound (2 circuit) Continuous Current Generator.

shown in Figs. 53 and 54. The winding shown in Fig. 53 is adopted when the ordinary lap winding would require an inconveniently small number of conductors and therefore of segments in the commutator. Fig. 54 shows the style of winding known as a wave winding. This style is often found in small dynamos as it requires fewer armature conductors than a lap winding to enable a given size of machine to produce a given electromotive force at a given speed.

Excitation.

The various methods used for supplying the current to the field coils (called the exciting current) are shown in Figs. 55 *a*, *b*, *c**. A shunt dynamo is one in which the field coils are connected between the positive and negative terminals of the dynamo, forming a separate circuit which takes a part of the current generated in the armature, as shown in Fig. 55 *a*. In this case the current used in the external circuit of the dynamo is less than the total current generated by the amount of the current used for

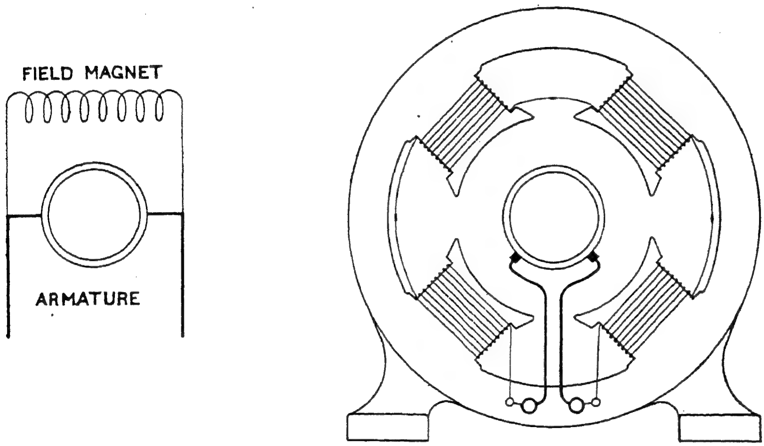


Fig. 55 *a*. Diagrams of Shunt Dynamo.

exciting the field coils, and it is important to have the exciting current as small as possible. Hence, the field coils are wound with a large number of turns of comparatively fine wire. The shunt dynamo gives approximately constant voltage at a constant speed; an adjustable resistance in the circuit of the field coils is often used as a means of regulating the voltage.

In a series dynamo the main current given out by the machine is taken round the field coils on its way to the external circuit (see Fig. 55 *b*) and the field coils consist of comparatively few turns of

* These are shown in their simplest diagrammatic forms on the left of the Figs. The right hand diagrams of these figs. illustrate the corresponding arrangements in rather more elaborate style.

stout copper conductor. When driven at a constant speed the series dynamo has a voltage roughly proportional to the current

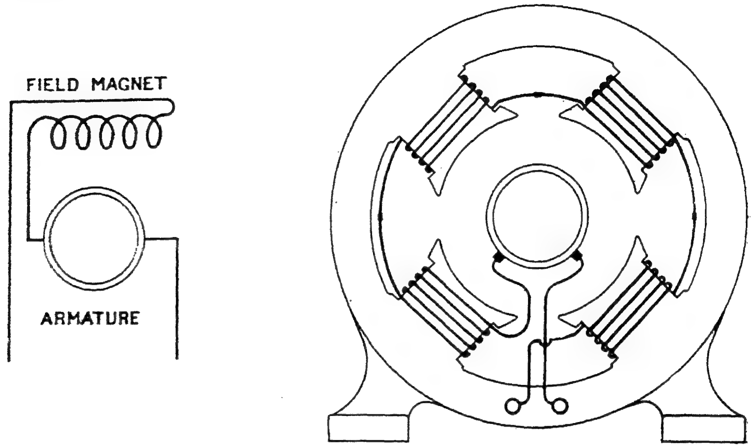


Fig. 55 *b*. Diagrams of Series Dynamo.

given out, and its use is therefore confined to certain special purposes (*e.g.* boosters).

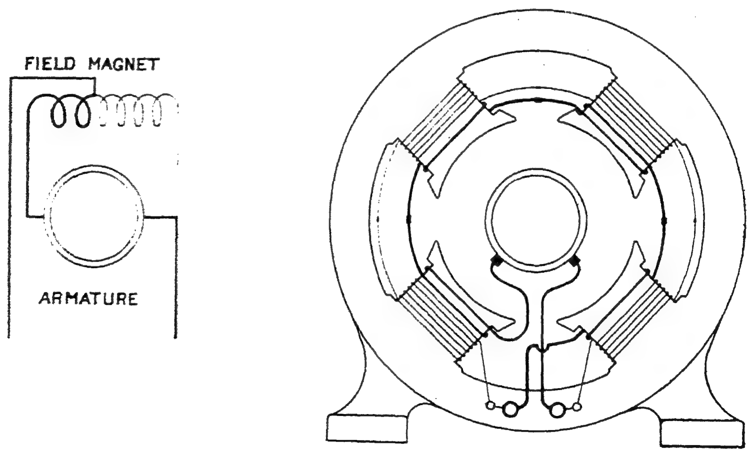


Fig. 55 *c*. Diagrams of Compound Dynamo.

The compound dynamo (Fig. 55 *c*) is a combination of shunt and series arrangements and is adopted largely in installations where a single machine is used at a time. This combination enables

a much more constant voltage to be obtained without the use of regulating devices.

To complete the list of methods of excitation we should include magneto machines and separately excited dynamos. In magneto machines the field magnet consists of one or more permanent magnets; such machines are in common use for ignition purposes in petrol engines and other internal combustion engines. A separately excited dynamo is one in which the current from the field coils is not supplied from the armature of the dynamo itself but from a separate source, such as another machine. Alternating current generators are generally separately excited, but this method of excitation is seldom used for continuous current machines.

Reactions.

The uninitiated are often at a loss to understand why a running dynamo requires so much power to drive it when they see nothing to impede the motion save an insignificant amount of friction. The currents in the armature conductors are in a magnetic field and, as already explained on page 48, are therefore subject to a force proportional to the amount of the current; in accordance with Lenz' Law, the force opposes the motion from which the currents ultimately originate. This explains the effort required to drive the armature.

The magnetic forces produced by the armature currents in a dynamo also have the effect of disturbing and somewhat diminishing the lines of induction of the dynamo and modifying its output accordingly.

As will be obvious from Fig. 51, the iron core of the armature of a running dynamo is moving in a magnetic field and each portion of it is cutting lines, thus producing electromotive forces within the core itself. These electromotive forces cause eddy currents to circulate in the iron core which also give rise to forces opposing the motion of the armature, but in their case the effort required to overcome their opposition to the motion is a waste of energy. Consequently it is important to reduce the eddy currents to the lowest practicable minimum. This is accomplished by constructing the armature core in such a manner as to make the

resistance in the paths of the eddy currents as great as possible without interfering with the passage of the magnetic lines through it. In practice the core of the armature is built up of thin discs of soft iron (about $\frac{1}{50}$ inch thick) separated by very thin layers of insulation (about $\frac{1}{200}$ inch thick).

It will be observed from Fig. 52 that when any one segment of the commutator passes one of the rows of brushes, the current in the conductors leading up to it is reversed. In accordance with Lenz' Law, the nature of the electromagnetic actions produced by the reversal of the current are such as tend to oppose this reversal and the current appears to endeavour to continue in its original direction. When sparking takes place at the brushes, it is accounted for by this cause (unless, of course, there is some defect in the armature) and it is cured by shifting the position of the brushes. The sparkless position of the brushes is reached when they are so placed that the reversal of the current in each section of the armature winding is accomplished by the electromotive force induced in it while the corresponding commutator segments are passing underneath the brushes.

Most dynamos have the brushes mounted on a brush rocker permitting of a ready adjustment of the position of the brushes, but it is seldom that the brushes of a modern dynamo require readjustment when once they are correctly placed. It is now fairly common to provide dynamos with small interpoles which are magnetised by series coils for the purpose of effecting commutation, that is, the reversal of the current in the sections as they pass the brushes.

Continuous Current Motors.

The electrical and magnetic features of continuous current motors are essentially the same as those of continuous current generators and the same machine can be used as either motor or generator. However, dynamos intended for use solely as motors are generally constructed so as to have their internal mechanism covered in or protected. This practice is dictated by purely mechanical considerations and only affects the mechanical design of the machine.

When a motor at rest is connected up to supply mains the current through it is determined solely by the voltage of the supply and the resistance in the motor circuit. As the resistance of the motor itself is always small, generally a fraction of an ohm, it is necessary to have some external resistance in series with the motor when starting it from rest in order to prevent the passage of an excessive current through it; hence the necessity for employing motor starters containing the requisite resistance.

When a motor is running the motion of the armature conductors in the magnetic field of the motor generates an electromotive force in the armature and, as may be inferred from Lenz' Law, this electromotive force opposes the electromotive force supplying current to the motor and is thus called the back E.M.F. of the motor. The current then passing through the motor is equal to

$$\frac{\text{E.M.F. applied to motor} - \text{back E.M.F. of motor}}{\text{resistance of motor}}.$$

The back E.M.F. is obviously proportional to the speed of the motor and therefore the current supplied to the motor becomes smaller and smaller as the speed increases so that the starting resistance should be gradually cut out as the motor gains speed.

As it is important to avoid the risk of starting a motor without a starting resistance in circuit, motor starters are provided with an automatic device to safeguard against such a contingency. The nature of the contrivance for accomplishing this is indicated in Fig. 56 which gives a diagrammatic view of a typical form of starter and connections, for use with a shunt wound motor.

The starter is manipulated by a handle H which occupies the position shown in the diagram when the motor is at rest and disconnected from the supply mains. To start the motor the main switch S is closed and the starting resistance R is gradually cut out by turning the handle H to the right. When H occupies the running position the whole of the starting resistance is removed from the motor circuit, but the handle is provided with a spring tending to force it back to the starting position. While the motor is in use the handle is kept in the running position by the little electromagnet E which is excited by the current in the motor's field coils with which it is in series, and which attracts a soft iron keeper fixed on

the handle *H*. Whenever the motor is stopped by opening the switch *S*, the current in the electromagnet *E* ceases to flow at the same time as the current in the motor itself and the spring restores the handle to the starting position. This same device also protects the motor against other contingencies, for example, a break in the

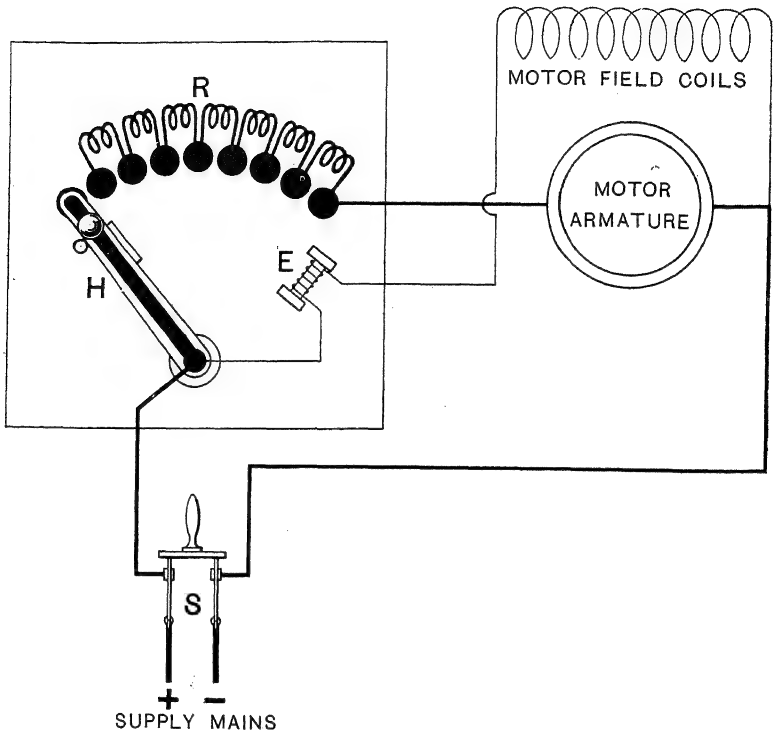


Fig. 56. Diagram of Motor Starter (Shunt Motor).

field magnet circuit. Additional contrivances are sometimes added to motor starters.

Motors—for purposes other than electric traction—are generally provided with simple shunt excitation. When the load on a running motor is increased, the speed falls slightly until the back E.M.F. is reduced sufficiently to allow the current to increase to the amount requisite to cope with the increased turning effort demanded. Similarly, when the load is diminished, the speed increases, but

the fluctuations of speed are small compared with the changes in the load.

Alternating Current Dynamos.

The majority of alternating current machines present features very distinct from those of continuous current dynamos; most types are without a commutator; in large generators it is frequently the field magnet which is made to revolve; and, in many alternating current motors the difference between the revolving and stationary parts of the machine is so slight from an electrical point of view, that it is necessary to distinguish them by the names "rotor" and "stator."

CHAPTER VI

MEASUREMENT OF RESISTANCE

One of the causes which have contributed to the phenomenal development of electrical science and its industrial applications during the past century is the facility with which it has been possible to make electrical measurements of *great delicacy and accuracy*. The measurement of resistance and the information which can be obtained from resistance measurements are without parallel in any other branch of technology, and it so happens that it is possible to compare resistances or to measure resistances in terms of a known standard or unit with greater accuracy than is possible in the case of any other kind of electrical measurement (or of most measurements in general). Hence measurements of other electrical quantities are frequently made to depend on resistance measurements—especially when great accuracy is desired.

Fall of Potential Method.

The most straightforward method of determining the resistance of any conductor is to connect it in series with one of known resistance, send a steady current through the pair and measure the differences of potential between the terminals of each resistance. The resistances are directly proportional to the corresponding differences of potential * (falls of potential), and the amount of the unknown resistance can be calculated from that of the known resistance by simple proportion. This method goes by the name of the "fall of potential" method and the arrangement is shown diagrammatically in Fig. 57.

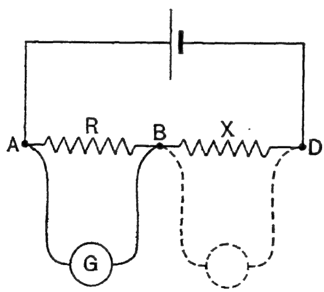


Fig. 57.

* For proof see page 22.

Instead of using a voltmeter to measure the falls of potential, a sensitive galvanometer of high resistance is generally preferred. This arrangement has the advantage that the current sent through the resistances may be made very small, thus avoiding errors arising from changes of temperature produced by the heating effect of the current. In any case it is essential that the resistance of the galvanometer or potential measuring device should be very great compared with that of either of the resistances used, in order that the amount of the current in the known and unknown resistances should not be appreciably disturbed by the measurement of the falls of potential. If the resistance of the galvanometer used is not sufficiently great, it suffices to add an adequate series resistance in the galvanometer circuit.

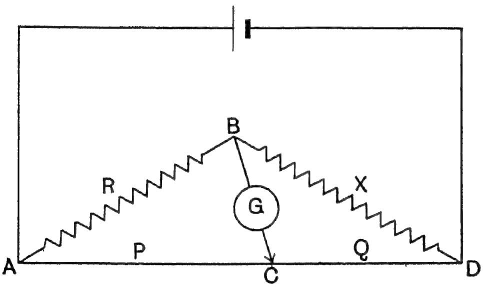


Fig. 58.

Wheatstone's Bridge methods have superseded the fall of potential method for everyday use. The fall of potential method is generally confined to special work, particularly measurements of " low " resistances such as rods or bars of metal, and even then special devices are frequently employed—for example, Kelvin's method of auxiliary conductors or Matthiessen and Hockin's method of projection of equi-potentials.

Slide Wire Bridge.

The slide wire bridge method of measuring resistance might be developed from the fall of potential method in the following manner. Connect a uniform wire in parallel with the pair of resistances which are being compared—as shown in Fig. 58, in

which R represents the known resistance, X, the unknown resistance and the straight line joining AD represents the uniform wire.

The current from the cell or battery will now be divided between the resistances R and X and the wire AD, but, nevertheless, the current in R will still be the same as the current in X and their resistances will be proportional to the respective falls of potential between their terminals. However, the wire AD provides a ready means of ascertaining the ratio of these falls of potential. Every point of the wire is at some potential less than A and greater than D, hence some point on the wire will have the same potential as the point B. This point can be found by connecting one terminal of a galvanometer to B and moving the other terminal along the wire until the point is found *at which there is no current whatever through the galvanometer*.

When that point is found (call it C) the galvanometer connection between B and C makes no disturbance in the currents in the various resistances, and the potential at C being the same as the potential at B, the required differences of potential are the difference of potential between A and C and the difference of potential between C and D. These, in their turn, are proportional to the resistances of the lengths of wire AC and CD, since the same current passes every section of the wire; and as the wire is uniform these resistances will be proportional to the respective lengths of wire. Hence, finally, we have the ratio of the resistances of R and X the same as the ratio of the lengths of wire in AC and CD, from which the unknown resistance can be determined by simple proportion.

The principle of this method was devised by Sir Charles Wheatstone and goes by the name of Wheatstone's Bridge. There are several forms of apparatus working on the Wheatstone's Bridge principle.

The arrangement just described has the following advantages over the simple form of fall of potential method:

(1) The sensitiveness of the determination can be readily increased by using greater lengths of wire (between A and D).

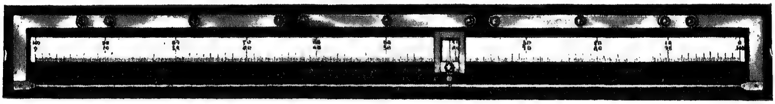
(2) * The galvanometer is only used to indicate the presence

* When a galvanometer is only used to find the conditions in which there is no current through it, the experiment is described as employing a "null" method.

or absence of a current through it and can be used in a condition of the utmost sensitiveness. Consequently, the currents used may be small enough to render their heating effects quite negligible.

(3) No special precautions need be taken to ensure the constancy of the current from the cell or battery. (One cell is generally sufficient.)

In Wheatstone's Bridge determinations the only disturbing effect produced by fluctuations of the current from the cell is that due to induced currents arising therefrom. These will be inappreciable for the slow changes taking place in the current when



Slide Wire Bridge.

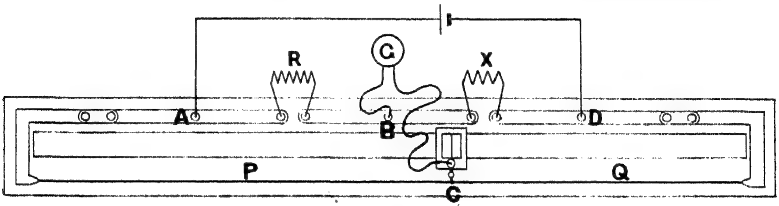


Fig. 50. Diagram of Slide Wire Bridge.

once started. To avoid the effects of the momentary induced currents set up at the moment of connecting or disconnecting the cell, it suffices to connect the cell before touching the wire with the galvanometer terminal.

It may be pointed out here that resistances used for purposes of measurement are generally wound "anti-inductively" or "non-inductively," as it is called, that is, the wire of which they are made is folded on itself before winding it into a coil. With a coil so wound any line of force cutting any part of the wire cuts

Null methods have the advantage that their accuracy is not dependent upon the use of a calibrated galvanometer.

The methods of Kelvin and Matthiessen and Hockin also possess the advantages enumerated under (2) and (3).

also the adjacent wire, thereby making equal induced electromotive forces in opposite directions in the coil, the net effect of which is nil.

The apparatus used for measuring resistances by the method just described is called a Slide Wire Bridge. The adoption of the word " slide " in this connection is explained by the manner in which the apparatus is used. The wire is generally made one metre long and the lengths of its parts read off from a metre scale fixed alongside. In this case the apparatus goes by the name of " Slide Metre Bridge." It is illustrated in Fig. 59.

If great sensitiveness is desired, the slide wire would require to be of great length. The practical inconvenience arising therefrom may be obviated by using a wire in metre sections, and all but one of these sections may be wound into coils suitably grouped at the ends of the stretched portion. (Terminals for this purpose are shown in Fig. 59. The thick copper strips connecting the various terminals on the slide metre bridge have a negligible resistance.) This device is now seldom employed as there are other forms of Wheatstone's Bridge more convenient to use when great accuracy is of importance.

// *Wheatstone Bridge Diagram.*

In Fig. 58 we may regard the wire AD as being made up of two resistances, namely, the resistance of AC (call it P), and the resistance of CD (call it Q). The arrangement then consists of four resistances P, Q, X, R, connected in a consecutive series with the cell connections dividing the group into one set of pairs and the galvanometer connections dividing the group into another set of pairs. In following out the connections of Wheatstone Bridge arrangements it will be convenient to remember that the essential features of the diagram of connection are that the unknown resistance and three others form a closed circuit, and that in passing round this closed circuit one encounters at the junctions between consecutive resistances a cell connection and a galvanometer connection alternately.

When the resistances are so adjusted that there is no current in the galvanometer (the current from the cell having previously

reached its steady state) the resistances are said to be " balanced " and then their magnitudes are related as follows :

$$P : Q = R : X.$$

$$\frac{P}{Q} = \frac{R}{X}.$$

$$X = \frac{RQ}{P}.$$

It follows from this relation that if we interchange R and Q we do not disturb the " balance " of the system. If we inter-

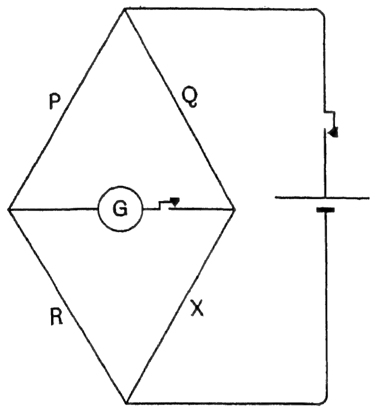


Fig. 60.

change R and Q in Fig. 58 and turn the diagram round, we see that it is in effect equivalent to interchanging the cell and galvanometer connections. This gives us the arrangement shown diagrammatically in Fig. 60 which is the usual form in which the Wheatstone Bridge diagram is represented.

Wheatstone Bridge Resistance Box.

The most commonly used apparatus for resistance measurement is a resistance box on the Wheatstone Bridge principle. There are many varieties of Wheatstone Bridge boxes, some of which are illustrated in Figs. 63 to 69, but the great majority are similar in their main features to that illustrated in Fig. 61.

The box arrangement differs from the slide wire bridge in this respect. Instead of using a fixed known resistance for R and a continuously adjustable ratio for the resistances P and Q, the ratio of P to Q is fixed (at some one of a few limited values) and the resistance of R is adjustable (through a whole series of known values). Incidentally, calculations are practically eliminated as the ratio of P to Q is always arranged to be some power of 10.

The Wheatstone Bridge resistance box has three sets of resistance coils. Two of these sets (called the ratio coils) contain coils of 1000, 100, and 10 ohms (sometimes also 1 ohm). The third set is provided with coils capable of being adjusted to any value from 1 ohm to 1000, 10 000, or even 100 000 ohms, as the case may be. The fourth resistance of the Bridge is the resistance to be measured.

The coils in the box are wound non-inductively on bobbins assembled on the under side of the cover. The ends of each coil are connected (silver soldered) to an adjacent pair of brass pillars screwed through the cover into short thick bars of brass arranged in rows on the upper surface of the cover.

When it is desired to exclude the resistance of any coil from the total of the set, the brass bars to which it is connected are short-circuited by a plug *. The number of ohms in each coil is indicated by a figure marked on the cover opposite the corresponding plug gap.

When a coil is "cut out" in this way, it is obvious that the coil and the plug are in parallel and as the combined resistance of two conductors in parallel is always less than that of the smaller resistance, and the resistance of a brass plug and block is of the order of a millionth of an ohm, it will be seen that no correction need be made for the resistance of the plugs and blocks themselves. It should be pointed out, however, that it is necessary that when a plug is inserted the "contact" should be good. This is effected by pushing the plug well home with a slight screwy motion. It should also be remembered that pulling a *plug out* puts the corresponding *resistance in* and inserting a plug removes the corresponding resistance.

* Dial pattern boxes not using the plug device are coming into more common use. For illustrations of dial boxes, see Figs. 66 to 69.

Fig. 62 shows the arrangement of the connections. As already pointed out, the galvanometer and cell connections may be interchanged, but it has been shown * that the most sensitive arrangement is obtained by connecting whichever of the galvanometer or the cell has the higher resistance to the junction of the two greatest resistances in the Bridge. In the conditions most

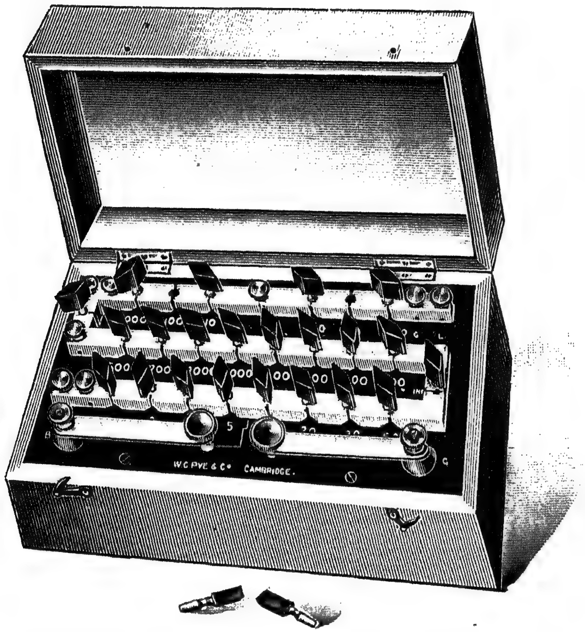


Fig. 61. Wheatstone Bridge Resistance Box.

frequently occurring in general practice, the most sensitive arrangement will be that shown in Fig. 62.

To save the trouble of making and undoing terminal connections every time the cell or galvanometer requires to be connected or disconnected, it is usual to have "tapper" keys in the circuits of the cell and galvanometer. These are generally provided on the box itself, and the connection between each key and the appropriate

* See Gray's *Absolute Measurements in Electricity and Magnetism*, Vol. 1, page 333.

place in the bridge is permanently made by a wire underneath the cover (as indicated by dotted lines in Fig. 62).

In measuring a resistance, the procedure is as follows. Make all the necessary connections in the manner indicated in Fig. 62. See that all plugs are securely inserted except one in each of the ratio coils. For a start it will generally be best to set both ratio coils at 100 ohms. Shunt the galvanometer so that it is not too sensitive. Press the cell key, then the galvanometer key carefully watching whether the galvanometer is deflected to the right or to the left. Then release the cell and galvanometer keys. To whichever side the galvanometer is deflected, you will know thereafter that a deflection to that side indicates that you have

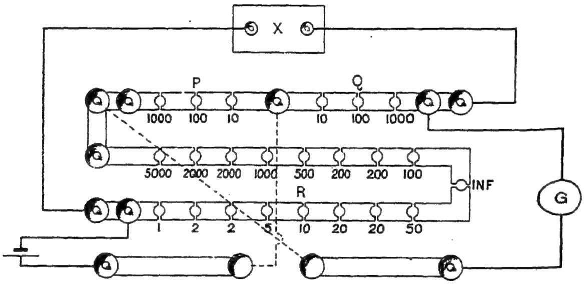


Fig. 62. Diagram of Wheatstone Bridge Resistance Box.

too little resistance in the adjustable "arm" of the bridge (previously denoted by the symbol R).

Some boxes have an "infinity plug" in the adjustable arm, that is a plug without a coil underneath which is a convenient way of obtaining an infinite resistance. If an infinity plug is provided, you may check the above by withdrawing the infinity plug, pressing the cell key, then pressing the galvanometer key and observing whether the galvanometer is deflected to the opposite side from before. If not, there is something the matter with your connections or some plug is loose, etc.

The remaining operations consist in repeated trials with various resistances in the adjustable arm until the amount which gives balance—*i.e.* no deflection in the galvanometer—is ascertained. When the adjustment has been carried far enough to get an

approximate value for the unknown resistance, the ratio coils may be altered (if advisable) to a more suitable proportion, and

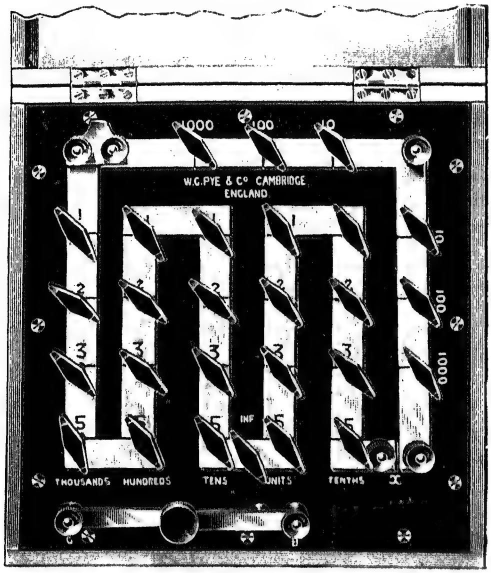


Fig. 63.

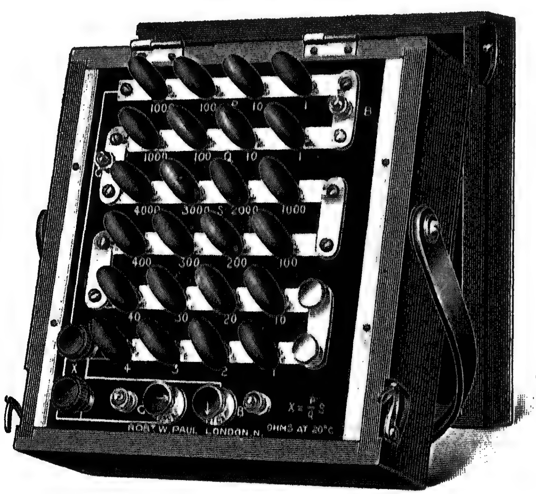


Fig. 64.

the determination then completed. In the final stages of the adjustment the galvanometer is used without a shunt, or at any

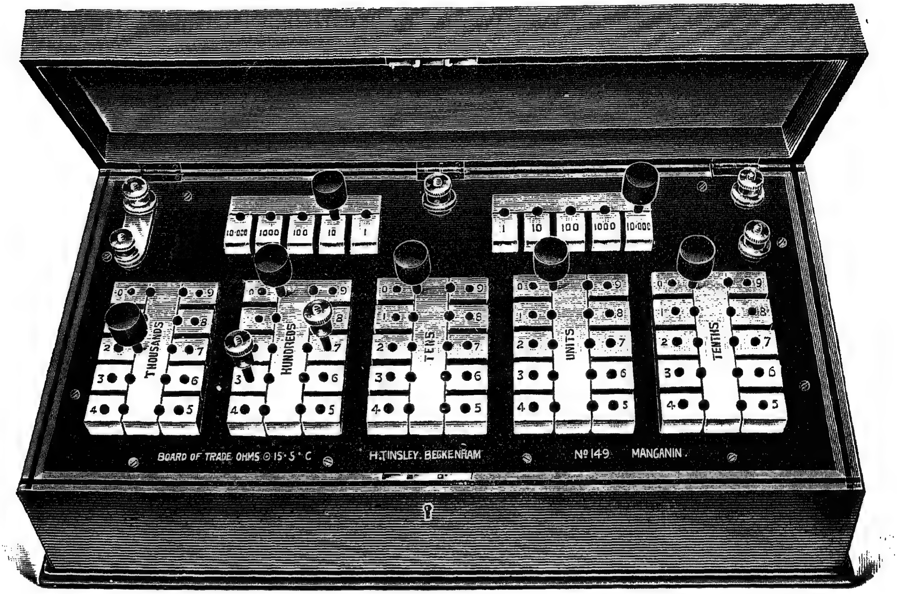


Fig. 65.

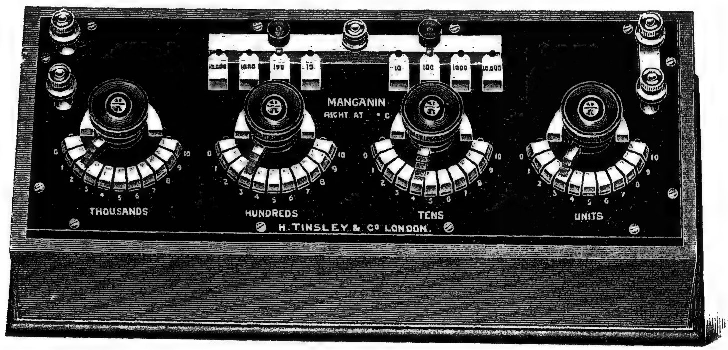


Fig. 66.

rate, with its sensitiveness increased to meet the necessities of the case.

It may happen that the position of absolute balance lies

between two consecutive resistances on the adjustable arm, for instance, it may be found that say 836 ohms in the adjustable arm

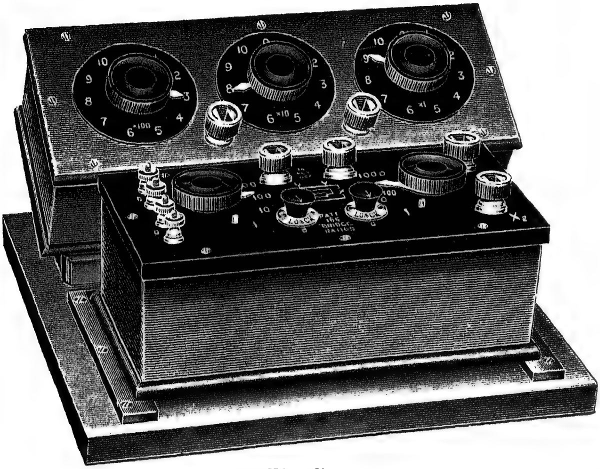


Fig. 67.

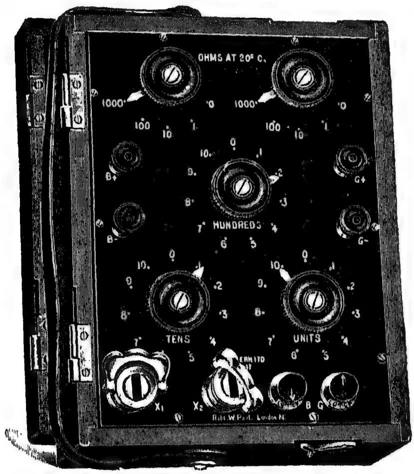


Fig. 68.

were too little and 837 ohms too much. The fractions of an ohm in a case like this can be obtained by observation of the deflections of the galvanometer. In the example cited, suppose the deflection

was 11 scale divisions to the right with 836 ohms and 19 divisions to the left with 837 ohms, the exact number would be

$$836 + \frac{11}{11+19} \text{ ohms, } i.e. \text{ } 836.37 \text{ ohms.}$$

Fractions of an ohm in the adjustable arm can be obtained in this way, by adding to the nearest resistance which is too low the ratio of the deflection obtained with this resistance to the sum of it and the deflection obtained with the adjustable arm set one ohm higher.

Precision Bridge Methods.

There are certain refinements necessary for great accuracy which we cannot do more than briefly indicate here. One is the use of a galvanometer of the utmost sensitiveness and another is the use of a slide wire in conjunction with the coils of the adjustable arm to read directly to small fractions of an ohm. See Fig. 69. It is also advantageous to use ratios which assist the sensitiveness of the adjustment of the balance. The sensitiveness of the Wheatstone Bridge is greatest when all its four resistances are equal. Hence some experimenters always make the resistances in the ratio coils equal. Another matter of consequence is to keep the box at a uniform temperature throughout, even although the coils are wound with wire having a small temperature coefficient of resistance. This is generally accomplished by having the interior of the box filled with an insulating oil and having an arrangement for keeping the oil stirred.

But the most important of all refinements for accurate work is the calibration of the resistance box, an operation which consists in determining accurately the precise resistance value of each coil in the box (and each division of the slide wire) or, at any rate, the precise ratios of their resistance values. This is generally a fairly laborious operation but several boxes have been constructed —such as Callendar and Griffiths' self-testing resistance box— which lend themselves readily to convenient calibration. When a box has been calibrated, the determination of the exact values of the resistances is made simply by an operation similar to using it to measure the resistance of a copy of the standard ohm. Boxes

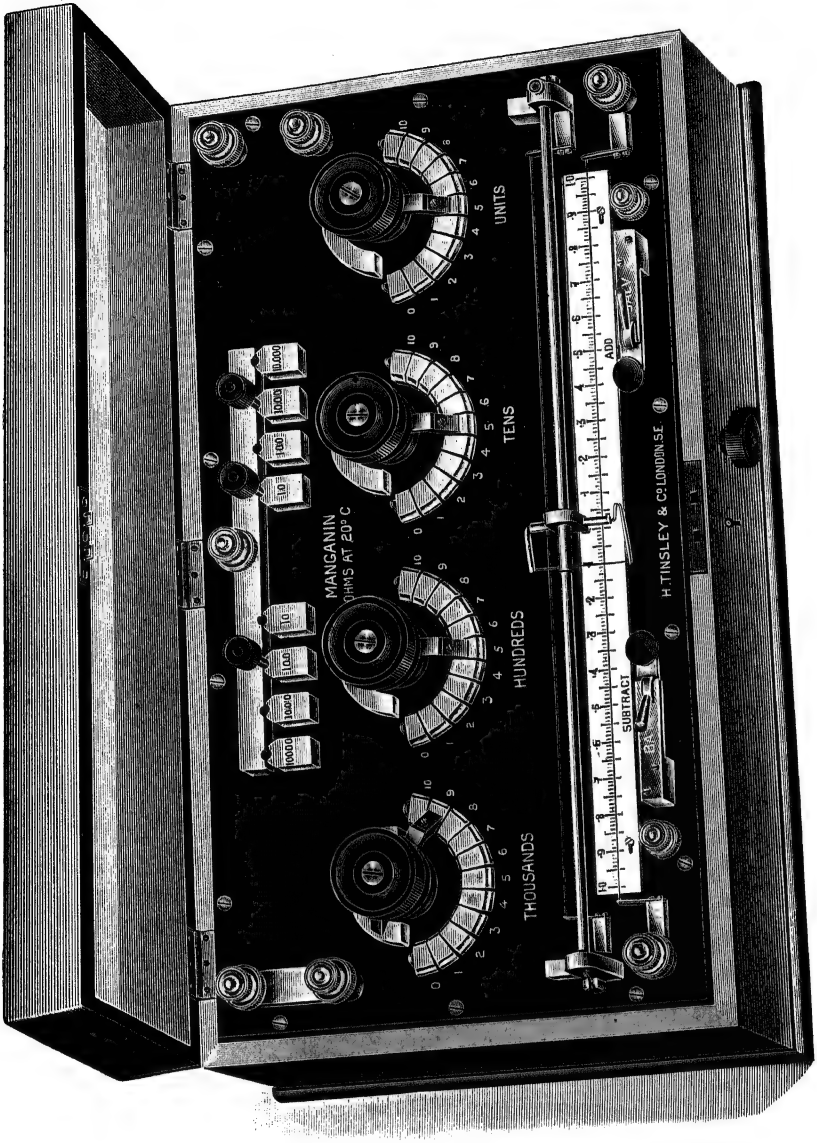

UNITS
TENS
HUNDREDS
THOUSANDS
MANGANIN
OHMS AT 20° C
ADD
SUBTRACT
H. TINSLEY & Co. LONDON. S.E.

Fig. 69.

provided with a slide-wire, as in Fig. 69, lend themselves more readily to the process of calibration.

The cheaper makes of resistance boxes are generally only adjusted to within 1 part in 500 or 1 part in 1000, but calibration renders a box of this accuracy quite as good as boxes adjusted with greater refinement, since it is no more trouble to make corrections for small errors than for *very* small errors.

Portable Testing Sets.

For tests (involving resistance measurements) in connection with electrical conductors in streets and buildings, it is necessary to have the apparatus in a convenient portable form. Portable testing sets working on the Wheatstone Bridge principle are made for localising "faults" in conductors and similar purposes, but Wheatstone Bridges are not used exclusively. Such sets generally have the resistances, microammeter and other accessories mounted together in one box.

One of the commonest kinds of "outside" tests is the measurement of insulation resistance, that is, the resistance between the conductor and the "earth." When insulation resistance is measured with a view to ascertaining its adequacy, it is important that the test be conducted with the insulation subjected to an adequate difference of potential on account of the fact that insulation which is ample to withstand a moderate difference of potential may break down utterly at a higher difference of potential (see page 19).

Very ingenious and convenient direct reading testing sets with an ohmmeter and generator in one portable case are now made for insulation resistance measurements. See Figs. 70, 74 and 76. (Of course, their use is not necessarily confined to insulation tests.)

The Megger.

The Megger, made by Evershed and Vignoles, works on the moving coil principle. As will be seen on reference to Fig. 71, the permanent magnets have two gaps. In one of these revolves the armature of the generator driven by hand by a handle at one end of the case. In the other gap are fine wire coils acting on

the same principle as the moving coil voltmeter and ammeter. In this instance, however, there are two such coils, a voltmeter coil and an ammeter coil, in vertical planes inclined to each other about 45°. The voltmeter or potential coil tends to move the

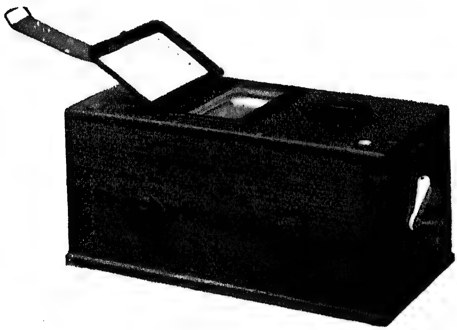


Fig. 70. The Megger.

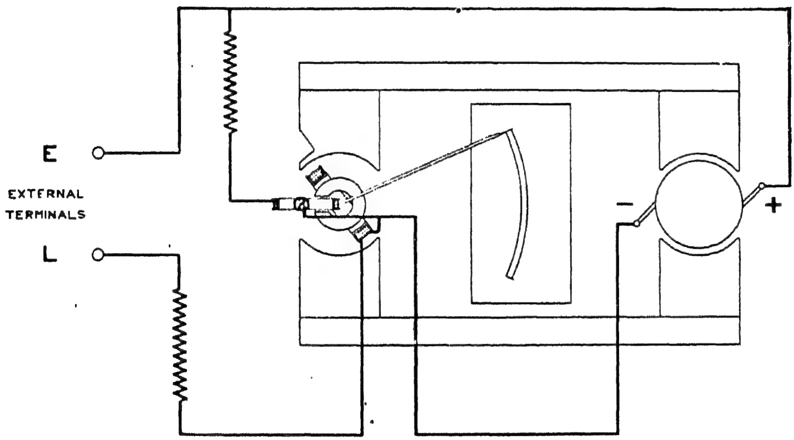


Fig. 71. Diagram of Meggor.

pointer in one direction and the ammeter or current coil tends to move the pointer in the opposite direction. The exact position which the pointer takes up depends upon the ratio of the forces of these two coils and therefore upon the resistance between the terminals which is read directly from the scale on the lid of the instrument.

Constant pressure Meggers are made which, by an ingenious clutch arrangement, give constant voltage when driven at any

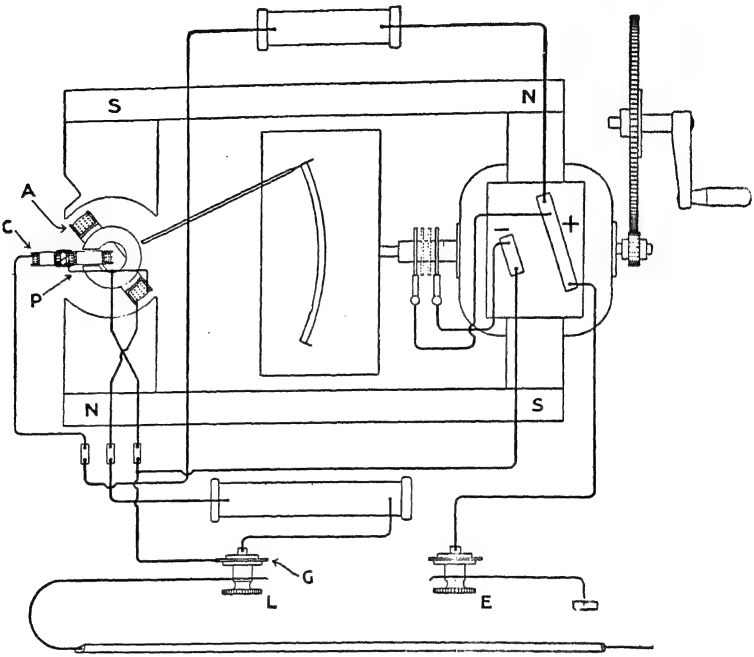


Fig. 72. Diagram of Megger.

speed above a certain amount. High range Meggers are provided with a " guard terminal " which is useful in eliminating the effect of surface leakage when making tests of the insulation resistance

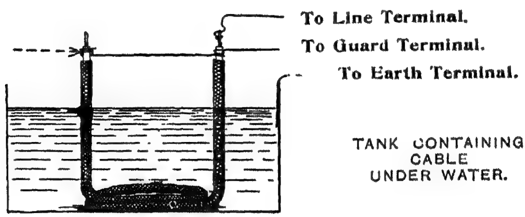


Fig. 73.

of a length of electric cable. Fig. 72 shows the diagram of connections of a Megger fitted with the guard terminal (as well as

giving greater detail of the internal arrangements than Fig. 71) and Fig. 73 shows the arrangement adopted in making a test of cable insulation.

Evershed and Vignoles also make other kinds of portable testing sets of which the Bridge-Megger, working on the Wheatstone Bridge principle, has a wide range of usefulness.

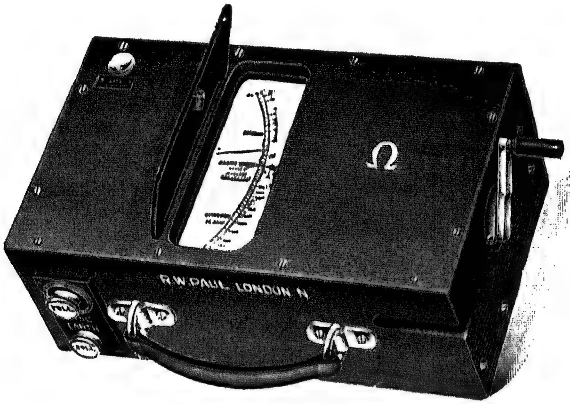


Fig. 74. The Omega.

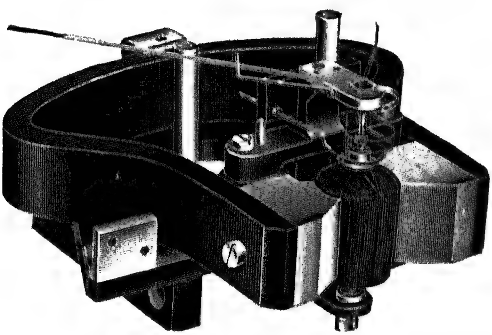


Fig. 75. Ohmmeter of Omega Testing Set.

The Omega.

The Omega, made by R. W. Paul, also works on the moving coil principle. In this testing set, the generator and ohmmeter parts of the instrument are each self-contained although fitted in the same case. The features of the moving coil system will be

readily seen from Fig. 75, and it will be noticed that the coils subtend a wide angle, enabling a large number of coil turns to be employed and admitting of a narrow and uniform air gap. This design gives the instrument the advantages of a long scale—subtending an angle of about 75°—and large working forces.

The Megohmmeter.

The Megohmmeter of Kelvin, Bottomley and Baird resembles the omega in all important features. Each instrument of this make is provided with a "Divide by Ten" key which, when depressed, changes the range of the instrument so that the true value of the reading is one-tenth of the indication.

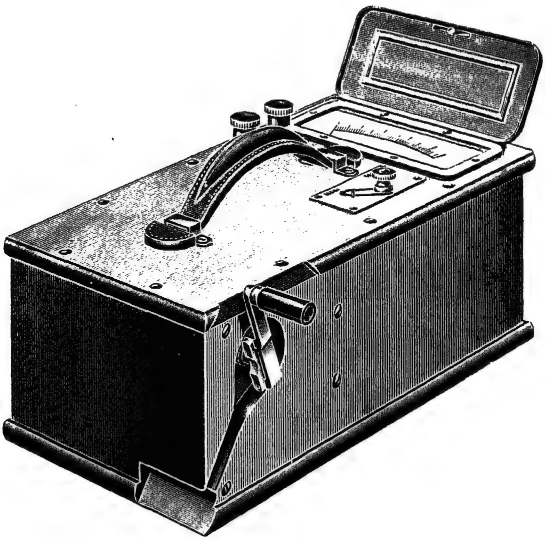


Fig. 76. The Ohmer.

The Ohmer.

The Ohmer, made by Nalder Bros. and Thompson, consists of an ohmmeter and generator mounted in one case. See Fig. 76. The ohmmeter is of the electrostatic type and its method of working may be gathered from the diagram given in Fig. 77. The generator has one of its terminals attached directly to one quadrant

A of the Electrostatic Ohmmeter, and the same terminal connected through a resistance *R* (which is wound on porcelain insulators and contained in the case of the instrument) to the other quadrant *B* of the Ohmmeter. The other terminal of the generator is connected to the vane *V*. The quadrant *B* is connected to the line to be tested and the vane *V* is connected to the earth. When the insulation resistance between the earth and line is infinite there is no current flowing through the resistance *R*, and the vane *V* takes up the position shown on the diagram. When a current flows from *E* to *L* there is a difference of potential between *A* and

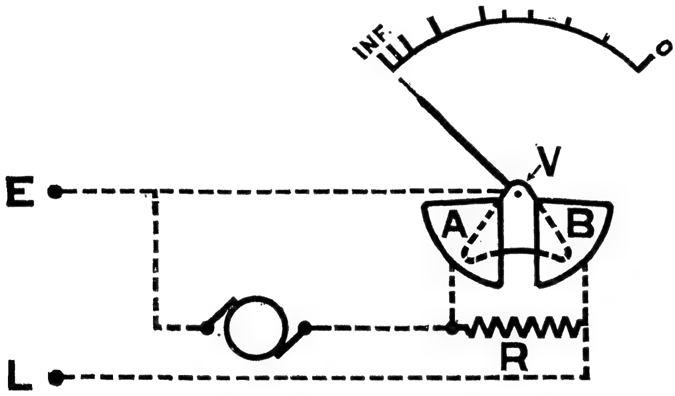


Fig. 77. Diagram of the Ohmer.

B due to the current flowing through *R*; consequently *A* and *B* are then charged with different amounts of electricity and the effects of their attractions on the electricity induced in *V* is to make it change its position. *V* then takes up a new position of equilibrium determined by the difference of potential (and the shape of the vane which is approximately as shown so as to be in stable equilibrium at all parts of the scale).

In the actual instrument there are four sets of quadrants, with 13 fixed vanes in each set; opposite sets are connected together; the moving vane consists of 12 vanes of mica covered with aluminium. The electrostatic ohmmeter renders the Ohmer testing set the lightest instrument of this description on the market.

Battery Resistance.

Resistance measurements of electrolytes (see page 18), voltaic cells or batteries, or circuits containing solutions are attended with special difficulties owing to the fact that their state is disturbed even by the small currents used in making a resistance determination. The disturbance is due to two causes, (1) change of resistance owing to change of chemical constitution, (2) electromotive forces set up in the solution itself by the products of decomposition. Of these, the latter is generally more serious.

There are two well known methods for finding the resistance of a simple electrolyte or solution but a perfect method still remains to be devised. Horsford's method consists in putting the elec-

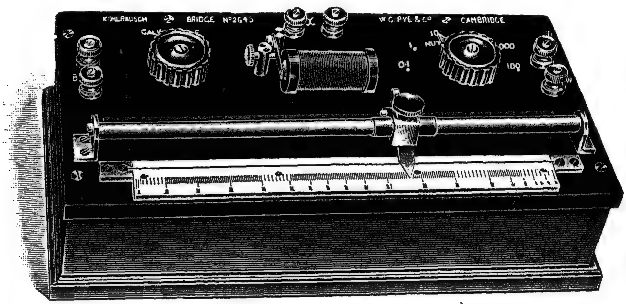


Fig. 78. Pye's Kohlrausch Apparatus.

trolyte in a long glass tube of uniform section through the ends of which are let in metallic rods ending in suitable metallic plates (called electrodes). The resistance is then found by the ordinary Wheatstone Bridge method. The experiment is then repeated with a shorter distance between the electrodes and the difference between the two resistances found is taken as the resistance of that part of the electrolyte between the two positions of the movable electrode. This method assumes that the electromotive force of the electrolyte is the same in the case of both measurements which is better than neglecting it entirely.

The method of Kohlrausch and Nippoldt also uses the ordinary Wheatstone Bridge but employs alternating current instead of continuous current. This renders it necessary to use some

alternating current generating device in place of a cell for supplying the current for the Bridge and a telephone ear-piece or alternate current indicator in place of an ordinary galvanometer. It is assumed that the reversal of the current at each alternation leaves the electrolyte unchanged. The condition of the electrodes is a matter of great consequence in all such measurements. They are often made of platinum coated with a deposit of black platinum, but it is necessary to adapt the electrode to the particular electrolyte under investigation. Fig. 78 illustrates an apparatus for applying the method of Kohlrausch.

The determination of the internal resistance of a voltaic cell or battery offers still greater difficulties on account of the prominence of its own electromotive force. It is fortunate that such determinations are not often required and then, as a rule, rough approximations suffice. Four methods have been devised.

1. Ohm's method.
2. Beetz' method.
3. Mance's method.
4. Fall of potential method.

Ohm's method consists in connecting the battery to a known resistance capable of carrying the current and measuring the current produced; then repeating the experiment with another known resistance. Let X be the unknown internal resistance of the battery, E its electromotive force, C' and R' the current and resistance in the first experiment and C'' and R'' the current and resistance in the second experiment, then

$$E = C' (R' + X) = C'' (R'' + X),$$

from which we obtain

$$X = \frac{C''R'' - C'R'}{C' - C''}.$$

Errors of observation have a disproportionate effect on the ratio of the differences between quantities and if the battery resistance is small it sometimes happens that this method gives the battery resistance as negative! However, it is convenient to carry out in practice and is quite good enough to ascertain whether the battery is in good condition, in so far as resistance measurements can throw light upon the subject.

Beetz' method is referred to in the footnote to page 143. It has no practical value.

Mance's method is an adaptation of the Wheatstone Bridge to find the resistance of a cell by using it to supply the current to the Bridge, but connecting it in the place of the unknown resistance. The experiment is troublesome unless the galvanometer is far from sensitive and is not of practical value.

The fall of potential method is the simplest and best. It can be used to study the variation of internal resistance while current is being given out and allows the current to be regulated at will. All that is necessary is to measure the full electromotive force of the battery when no current is being given out and the electromotive force or difference of potential between its terminals when giving out current. The current must be measured or the external

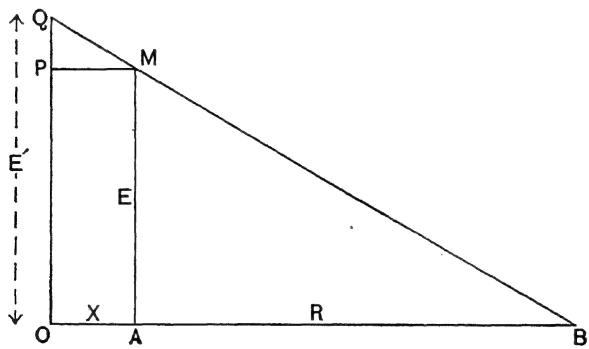


Fig. 79.

resistance must be known. Errors of observation will be less when the result is calculated from the amount of the external resistance if that is accurately known. Let X be the internal resistance of the battery, E' the difference of potential between its terminals when *not* giving out current, E the difference of potential between its terminals when supplying current C through an external resistance R, then

$$E' = C\,(R + X), \text{ and } E = CR \text{ (by Ohm's Law)},$$

hence
$$X = \frac{E' - E}{C} \quad \text{or} \quad X = R\,\frac{E' - E}{E},$$

from either of which the internal resistance can be calculated.

The above relationship between these quantities admits of simple graphical illustration. Let potential differences be marked off vertically and resistances horizontally as in Fig. 79, in which OQ represents the difference of potential E' when no current is passing, OP or AM the difference of potential when the current C is given out and AB represents the resistance R in the external circuit while OA ($= PM$) represents the internal battery resistance X. The sloping line QB shows how the potential falls throughout the entire circuit, and the amount represented by PQ is that part of it accounted for by the battery resistance. It is obvious from the figure that PQ is to PM as AM is to AB,

that is
$$E' - E : X = E : R,$$

or
$$\frac{X}{R} = \frac{E' - E}{E}.$$

Temperature Coefficient of Resistance.

The rate at which the resistance of a specimen changes with temperature is called its temperature coefficient of resistance which is defined as the increase of resistance per degree rise of temperature per ohm at zero temperature. As a rule, the increase of resistance is not absolutely the same for each degree of temperature rise, but it is sufficiently accurate for electrical engineering purposes (with a few important exceptions such as platinum resistance thermometry) to act on the assumption that the temperature coefficient is a constant quantity for each material. Moreover, when the resistance at zero temperature is not known but the resistances at two other temperatures are known, one of which is not far from zero—for example, the temperature of the air at the time—it is generally sufficiently accurate to take the temperature coefficient as the difference between the two resistances divided by that at the lower temperature and divided by the difference between the temperatures.

It is taken for granted that temperatures are measured on the Centigrade scale. The temperature coefficient in terms of the Fahrenheit degree is five-ninths of that in terms of the Centigrade degree. The Fahrenheit scale has nothing to commend its use in engineering or scientific work and its proper place is on the scrap heap.

The experimental determination of temperature coefficients (outside of an exhaustive research) is accomplished simply by measuring the resistance of a specimen at two different temperatures, the temperatures themselves also being measured. The principal trouble in this experiment is maintaining the specimen at a uniform steady temperature throughout the time occupied in the resistance measurement. It facilitates the accomplishment of this requirement to have the specimen immersed in a vessel of insulating oil which is kept stirred. It is convenient to take the temperature of the room as one of the temperatures at which the resistance is measured as this enables temperature regulating devices to be dispensed with, so far as one measurement is concerned. All the same, it is not difficult to make a measurement at zero temperature as this only requires the vessel containing the specimen and insulating oil to be immersed in melting ice for a sufficient time, the stirring process being, of course, always attended to. For temperatures outside these limits it is necessary to provide some heating arrangement and the simplest to work, considering the importance of maintaining a steady temperature, is a steam heater. If the vessel containing the specimen is placed inside a double jacket through which steam is passed at the boiling point, there will be no difficulty in keeping the specimen at a fixed temperature (near 100° C.) for any reasonable length of time. The stirring process is even more important at such a temperature than near ordinary temperatures. The temperatures can be conveniently read by means of an ordinary mercury-in-glass thermometer.

The method of calculating the temperature coefficient from the results of such an experiment has been given above. Numerical examples will be found at the end of the chapter.

Sometimes it is required to calculate the rise of temperature of a coil or conductor from the "hot" and "cold" resistances, the temperature coefficient of the material being known. This is obtained by dividing the increase of resistance by the "cold" resistance and by the temperature coefficient.

The exact relations between these quantities can be expressed by very simple formulae as follows.

Let α be the temperature coefficient of resistance,

Let R_0 be the resistance at zero temperature,

Let R_t be the resistance at temperature t,

then the definition of the temperature coefficient informs us that

$$\alpha = \frac{R_t - R_0}{tR_0},$$

and therefore also

$$t = \frac{R_t - R_0}{\alpha R_0}, \qquad R_t = R_0 (1 + \alpha t).$$

The approximations which we have already given for the case when R_0 is not known, but R_θ the resistance at temperature θ, not far from the zero, is known instead, are represented in symbols thus

$$\alpha = \frac{R_t - R_\theta}{(t - \theta) R_\theta}, \qquad t - \theta = \frac{R_t - R_\theta}{\alpha R_\theta}.$$

The exact* expression for α in terms of these quantities is

$$\alpha = \frac{R_t - R_\theta}{tR_\theta - \theta R_t},$$

which enables α to be calculated as accurately as if R_0 were known. For the temperature rise, the exact expression is

$$t - \theta = \frac{R_t - R_\theta}{\alpha R_\theta} (1 + \alpha\theta),$$

which shows that the exact temperature rise is obtained by multiplying the result obtained from the approximation by multiplying it by $1 + \alpha\theta$; if θ is not accurately known it may still be possible to enhance the accuracy of the result if an approximate guess for the value of θ can be made. (A number of temperature coefficients are given on page 15.)

Resistivity. (*Specific Resistance.*)

It has been pointed out already on page 12 that the resistivity of a substance is determined by measuring the resistance of a specimen of uniform cross-sectional area and dividing the measured resistance by the length of the specimen and multiplying by the cross-section.

* That is, as exact as is possible on the assumption of a constant temperature coefficient.

In the case of metals it sometimes happens that the tested specimen has a square or rectangular section ; the width and thickness can then be measured by means of a screw gauge and their product gives the cross-section. Round wires of circular section are most frequently met with ; in their case the diameter is measured with a screw gauge and the cross-section calculated from that ; the cross-section is $\frac{\pi}{4}$ times the square of the diameter. Where calculations of this kind are made with frequency, a table of circular areas is sometimes employed. Such calculations are almost child's play on the slide rule.

Copper wires play so important a part in electrical work that special tables are drawn up for them. In so far as concerns the diameters and sectional areas given in such tables for wires of the various gauge numbers, they are applicable to wires of any material and they can often supply the electrical engineer with the particulars sought in tables of circular areas. Also, the resistance data given in copper wire tables can often be utilised for calculations in connection with wires not made of copper. For example, suppose we require the resistivity of a wire 4 yards long having a resistance of 1.49 ohms and a diameter of 48 mils (a mil is one-thousandth of an inch), *i.e.* .048″. Instead of proceeding to work out

$$\frac{1.49 \times \frac{\pi}{4} \times (.048)^2}{4 \times 36} \quad \text{or} \quad \frac{1.49 \times \pi \times (.048)^2}{4 \times 4 \times 36}, \qquad (= 18.2 \div 10^6)$$

we can proceed as follows : look up the wire in the copper wire table (see page 131) which has a diameter of .048″ and we find it is No. 18 ; No. 18 copper wire has 13.28 ohms per 1000 yards ; the wire under investigation has $\frac{1.49 \times 1000}{4}$ (= 372.5) ohms per 1000 yards; therefore the wire has a resistivity $\frac{372.5}{13.28}$ times that of copper*. $\left(\frac{372.5}{13.28} \times .668 = 18.2.\right)$

* The resistivity of copper on which copper wire tables are based is .668 microhms per inch cube or 1.696 microhms per cm. cube. See page 130.

A problem which often presents itself is that of cutting off a length of wire which will have a given resistance—with a margin but not a wasteful margin for subsequent refined adjustment. In this case it is advisable to measure the resistance of a known length of the wire and calculate the length required for the given resistance by simple proportion. When it is necessary to work out the required length from the resistivity, there is no simpler method than using copper wire tables to find out the length of copper wire of the same diameter which would have a resistance equal to the specified amount divided by the ratio of the resistivity of the given material to that of copper.

The formulae for the relationships between the resistivity (ρ), length (l), cross-sectional area (s) and resistance (R) of a conductor are

$$\rho = \frac{Rs}{l}, \quad R = \frac{\rho l}{s}, \quad l = \frac{Rs}{\rho}, \quad s = \frac{\rho l}{R}.$$

In using these formulae it is important to see that all dimensions are in terms of the same unit and not to mix up centimetres with square millimetres, etc. Also, if the resistance is taken in ohms, the resistivity will be in ohms per cm. cube or ohms per inch cube as the case may be; if a resistance is calculated from a resistivity in microhms per cm. or inch cube, the resistance will be found in microhms.

Copper Conductors.

Copper is almost exclusively used commercially for conductors of electricity, on account of its small specific resistance. Silver would be too expensive. Impurities in copper increase its resistance, so that for electrical work the purity of the copper is important. It is now refined by electrolytic processes which produce very pure copper, but it would not pay to strive for the purity of the specimen referred to on page 15. For commercial use certain standards have been fixed by the Institution of Electrical Engineers Committee on Copper Conductors. The standard allowance for conductivity is called 100% conductivity, and the conductivity of all samples is expressed as a percentage

of this. The standard specific resistances at 60° F. are .000 000 667 88 ohms per inch cube or .000 001 696 39 ohms per cm. cube for annealed copper, and .000 000 681 327 ohms per inch cube or .000 001 730 54 ohms per cm. cube for hard-drawn wires. Clarke, Forde, and Taylor's results were adopted for the variation of the resistance of copper with temperature. These are embodied in the following formula for the ratio of the resistance of copper at $t°$ C. to its resistance at 0° C. :—

$$1 + .004\,267\,44\,t + .000\,001\,119\,3\,t^2.$$

The following tables are calculated from these data.

Resistivity of Copper (100 %).

		Annealed		Hard Drawn	
Deg. Cent.	Ratio to resistance at 0° C.	Microhms per cm. cube	Microhms per inch cube	Microhms per cm. cube	Microhms per inch cube
0	1.000 00	1.591	.6265	1.623	.639
5	1.021 38	1.625	.6395	1.657	.6525
10	1.042 78	1.659	.653	1.692	.666
15	1.064 25	1.693	.6665	1.727	.680
20	1.0858	1.727	.680	1.763	.694
25	1.1074	1.761	.6935	1.798	.7075
30	1.1290	1.795	.707	1.833	.7215
35	1.1507	1.830	.7205	1.869	.7355
40	1.1725	1.865	.734	1.904	.749
45	1.1953	1.900	.748	1.940	.763
50	1.2162	1.934	.7615	1.975	.777
55	1.2381	1.969	.775	2.010	.791
60	1.2601	2.004	.789	2.045	.805
65	1.2821	2.039	.8025	2.081	.819
70	1.3042	2.074	.816	2.117	.8335
75	1.3263	2.109	.830	2.153	.8475
80	1.3485	2.145	.844	2.189	.8615
85	1.3707	2.180	.858	2.225	.876
90	1.3930	2.215	.872	2.261	.890
95	1.4154	2.251	.886	2.298	.9045
100	1.4379	2.287	.900	2.335	.919

Copper Wire Table

Size No.	Diameter Inch	Diameter M/m	Sectional area Sq. Inch	Sectional area Sq. M/m	Lbs. per 1000 yards	Ohms per 1000 yards at 60° F.
0	.324	8.230	.082 45	53.19	953.4	.2917
1	.300	7.620	.070 69	45.60	817.6	.3402
2	.276	7.010	.059 83	38.60	692.0	.4019
3	.252	6.401	.049 88	32.18	576.7	.4821
4	.232	5.893	.042 27	27.27	488.8	.5688
5	.212	5.385	.035 30	22.77	408.2	.6813
6	.192	4.877	.028 95	18.68	334.7	.8307
7	.176	4.470	.024 33	15.70	281.3	.9881
8	.160	4.064	.020 11	12.97	232.5	1.195
9	.144	3.658	.016 29	10.501	188.4	1.476
10	.128	3 251	.012 87	8.303	148.8	1.868
11	.116	2.946	.010 57	6.819	122.2	2.275
12	.104	2.642	.008 495	5.480	98.24	2.831
13	.092	2.337	.006 648	4.289	76.88	3.617
14	.080	2.032	.005 027	3.243	58.13	4.784
15	.072	1.829	.004 072	2.627	47.09	5.904
16	.064	1.626	.003 217	2.075	37.20	7.478
17	.056	1.422	.002 463	1.589	28.48	9.762
18	.048	1.219	.001 810	1.168	20.93	13.28
19	.040	1.016	.001 257	.8109	14.53	19.13
20	.036	.9144	.001 018	.6567	11.77	23.62
21	.032	.8128	.000 804	.5188	9.301	29.90
22	.028	.7112	.000 616	.3973	7.120	39.05
23	.024	.6096	.000 452	.2919	5.233	53.13
24	.022	.5588	.000 380	.2453	4.392	63.24
25	.020	.5080	.000 314	.2027	3.633	76.53
26	.018	.4572	.000 254	.1642	2.942	94.48
27	.0164	.4166	.000 211	.136 28	2.440	113.8
28	.0148	.3759	.000 172	.110 99	1.989	139.8
29	.0136	.3454	.000 145	.093 72	1.676	165.5
30	.0124	.3149	.000 121	.077 91	1.399	199.1
31	.0116	.2946	.000 106	.068 18	1.222	227.5
32	.0108	.2743	000 091 6	.059 10	1.059	262.5
33	.0100	.2540	.000 078 5	.050 67	.9085	306.1
34	.0092	.2337	.000 066 5	.042 89	.7688	361.7
35	.0084	.2134	.000 055 4	.035 75	.6406	433.9
36	.0076	.1930	.000 045 4	.029 27	.5249	530.0
37	.0068	.1727	.000 036 3	.023 43	.4197	662.0
38	.0060	.1524	.000 028 3	.018 24	.3272	850.3

To obtain external diameter of cotton covered wires.

	D.C.C. (fine)	D.C.C. (ordinary)	Braiding (fine)
All sizes to No. 18	add 8 mils	add 10 mils	add 15 mils
Nos. 17 to 13	,, 10 ,,	,, 12 ,,	,, 18 ,,
No. 12 and larger	,, 12 ,,	,, 14 ,,	,, 22 ,,

EXERCISES ON CHAPTER VI

Temperature Coefficient.

50. Find the temperature coefficient of the metal (zinc) of which a strip has been made having a resistance of .575 ohms at 0° C. and .6925 ohms at 50° C.

Answer. Temp. coefft. $= \dfrac{.6925 - .575}{50 \times .575} = .00409.$

51. The field magnet coils of an alternating current generator take a current of 1.95 amp. when connected up at the temperature of the air to their supply circuit. After some time, owing to the coils heating, the current finally settles down to 1.83 amp. at the original voltage. Find the average temperature rise of the copper in these field magnet coils.

Answer. The resistance is inversely proportional to the current, so that for each ohm at the temperature of the air there is $\dfrac{1.95}{1.83}$ ohm at the "hot" temperature, therefore the temperature rise is (in centigrade degrees)

$$\frac{\dfrac{1.95}{1.83} - 1}{.004\,28 \times 1} = \frac{.0655}{.00428} = 15.3.$$

If the temperature of the air was 15° C.—and it would not be far from that—a closer approximation to the temperature rise would be

$$15.3 \times (1 + .00428 \times 15) = 15.3 \times 1.064 = 16.3.$$

52. Calculate the resistivity of aluminium at 50° C.

Answer. The required resistivity is

$$2.66\,(1 + .004\,35 \times 50) = 2.66\,(1 + .2175) = 3.24.$$

53. Find the temperature coefficient of a conductor that carries 3.06 amp. at 12 volts at temp. 19° C. and carries 11.4 amp. at 50 volts at temp. $44\frac{1}{2}$° C.

54. A resistance box having its coils wound with platinum-silver wire is correct at 17° C. What is the percentage error made in using it at 6° C. without making any temperature corrections ?

55. When a rheostat wound with iron wire had a constant voltage applied to it, the current was observed to diminish gradually from 31.4 amperes at starting with the temperature at 16° C. to 25.7 where it remained steady. Calculate approximately the temperature which was reached by the iron wire in the rheostat, assuming its temperature coefficient to be .006 25.

56. What must be the resistance of a platinum wire at 0° C. in order that its resistance may increase by a hundredth of an ohm for each degree (cent.) rise in its temperature ?

Resistivity.

57. The resistance of 10 yards of round brass wire .036 inch diameter is 1.057 ohm. Calculate the resistivity of the brass.

Answer. The resistance of the wire is 1 057 000 microhms.
The cross-section of the wire is $\frac{1}{4}\pi\ (.036)^2$ or .001 018 (sq. inch).
The length of the wire is 360 inches.
The resistivity in microhms per inch cube is therefore

$$\frac{1\ 057\ 000 \times \cdot 001\ 018}{360} = 2.99.$$

(This result might be obtained otherwise by use of the Wire Table on page 131. Wire with a diameter of .036″ is No. 20 and that size of copper wire has a resistance of 23.62 ohms per 1000 yards. The brass wire has 1.057 ohms for 10 yards or 105.7 ohms per 1000 yards and therefore has 105.7/23.62 or 4.47 times the resistivity of copper. The required resistivity is therefore $4.47 \times .668$ or 2.99 microhms per inch cube.)

58. Find the resistance of the suspension of a moving coil galvanometer consisting of a phosphor bronze strip 2 inches long, 1 mil thick and 10 mils wide, the specific resistance of the phosphor bronze being 2.2 times that of copper.

Answer. Resistivity of phosphor bronze $= 2.2 \times .668$ microhms per inch cube
$= 1.47$ microhms per inch cube.
Length of ,, ,, $= 2$ inches.
Cross-section of ,, ,, $= .001 \times .01$ sq. inch
$= .000\ 01$,,
therefore Resistance of ,, ,, $= \dfrac{1.47 \times 2}{\cdot 000\ 01}$ microhms
$= 294\ 000$,,
$= .294$ ohms.

59. What length of copper wire .004 square inch in section has a resistance of 1 ohm?

Answer. Length = resistance × cross-section ÷ resistivity
$= 1\ 000\ 000 \times .004 \div .668$ (inches)
$= 6000$ inches $= 500$ feet.

60. An ammeter shunt which is to have a resistance of 1/333 ohm is to be made from a strip of manganin 2 cm. wide and 1 mm. thick. What length must be cut off for this shunt?

Answer. 14.3 cm. plus a margin for adjustment and fixing.

61. Find the diameter of round eureka wire having a resistance of 1 ohm per 5 feet of length.

Answer. Cross-section = resistivity × length ÷ resistance
= 18.7 × 60 ÷ 1 000 000 square inches
= .001 122 square inches.

Diameter = square root of 4 × cross-section ÷ π
= „ .001 43 (inches)
= ~~.0378 inch~~. 0·012 inches.

62. The coil of a moving coil voltmeter has 100 turns of silk covered copper wire, the diameter of the wire when bare being .002 inch. The mean length per turn of the coil is 3.87 inches. Find the resistance of the coil.

63. Find the resistance of 1 metre of manganin wire one square millimetre in section.

64. Find the cross-section of iron wire which has a resistance of 4 ohms per 10 metres. *Ans.* .2495 sq. mm.

65. Find the resistance of 100 yards of eureka wire .0032 sq. inch in section.

66. What length of manganin wire .036 inches in diameter would be required for making a resistance coil of 10 ohms ?

67. What thickness would a plate of retort carbon 10 cm. × 8 cm. require to be to have a resistance of 500 microhms between its faces ?

Answer. .0005 × 80 ÷ .067 = .6 (cm.).

68. A strip of iron 1/2 inch wide and 1/64 inch thick is wound into a disc-shaped coil with a strip of insulation 1/64 inch thick between the layers of iron. Find the diameter of a coil consisting of 1 roll which has a resistance of 1.33 ohm.

(The diameter of the coil is the square root of $4/\pi$ times the length of the strip ÷ 32.)

69. The copper connections in a piece of apparatus have a total length of 20 feet and the section of the wire used is .0018 sq. inches. What is the total resistance of these connections ?

Battery Resistance.

70. The E.M.F. of a cell on open circuit is 1.62 volts. When connected in series with a 10 ohm coil and an ammeter of .01 ohm resistance, the current is .157 amps. Find the resistance of the cell.

Answer. $X + 10 + .01 = 1.62/.157 = 10.32$, which gives $X = .31$ ohms.

71. A cell connected to a high resistance mirror galvanometer produces a reading of 41.8 divisions. When a resistance of 20 ohms is connected in parallel with the galvanometer the reading is reduced to 37.4 divisions. What is the resistance of the cell ?

Answer. The galvanometer in this case may be treated as a voltmeter and hence

$$X = 20\,(41.8 - 37.4)/37.4 = 2.35 \text{ (ohms)}.$$

72. A Daniell cell is connected up to a voltmeter of 1000 ohms resistance, and its E.M.F. is seen to be 1.08 volts. Without disturbing these connections a resistance of 10 ohms is connected between the terminals of the cell. The voltmeter then reads 1.055 volts. Find the internal resistance of the cell.

73. A storage battery of 60 cells has a voltmeter and ammeter permanently connected in circuit. At a certain time the voltmeter read 112.5 volts, the ammeter at the same instant reading 47.5 amps. The current was switched off long enough to observe that with the current at zero the voltmeter read 118 volts. Calculate the internal resistance of the battery at the time these readings were taken.

74. The E.M.F. of storage cells drops about 10 % when they are discharging at the rate of $2\frac{1}{2}$ amp. per sq. ft. of positive plate. From this make an estimate in round numbers of the internal resistance of a storage cell having positive plates of a total area of 10 sq. ft.

75. Twelve cells each with an E.M.F. of 1.6 volts and an internal resistance of .25 ohms are put up into two batteries of 6 each, and these two batteries are put in parallel. What is the total E.M.F. and the total internal resistance of this combination of cells ?

76. Four cells, each having an E.M.F. of 1.56 volts and an internal resistance of .32 ohm, are being used in series to supply current to a circuit of 2 ohms resistance. What is the fall of potential over the 2 ohm resistance ?

77. A battery of cells when connected to a resistance coil of 10 ohms gives 3.20 amperes, and when another coil of 10 ohms is added in series with the former the current is reduced to 1.75 amperes. Find the resistance of the battery. (See page 123.)

78. A battery having an E.M.F. on open circuit of 10.3 volts is connected to a circuit of 5.00 ohms resistance, and produces in it a current of 1.92 amperes. What is the resistance of the battery ?

79. Five storage cells connected in series have a voltmeter connected to the extreme terminals. When there is nothing else in circuit the voltmeter reads 10.3 volts. When the cells are connected to an external circuit of 5 ohms resistance the voltmeter indicates 9.6 volts. Calculate the average internal resistance per cell.

Miscellaneous Questions on Chapter VI.

80. Explain the principle of the Wheatstone Bridge, and sketch the diagram of connections. (C. and G. 1913.)

81. Explain the principle and method of measurement of resistance by the Wheatstone Bridge, and give a diagram of connections. (C. and G. 1912.)

82. A motor speed regulator is divided into 10 resistance sections or steps ; how would you measure the resistance of each section by means of an ammeter and voltmeter ? Illustrate your answer by means of a diagram. (C. and G. 1910.)

83. Describe any method other than the above by which resistances may be measured, and say if you would use the same method for both high and low resistances. (C. and G. 1910.)

84. You are given a tangent galvanometer, having a resistance of 20 ohms, a rheostat and a Leclanché cell. The cell is joined in series with the galvanometer and rheostat, in which 227 ohms are inserted. A deflection of 40 tangent divisions is obtained. By increasing the resistance in the rheostat to 477 ohms the deflection is reduced to 20 tangent divisions. What is the internal resistance of the battery ? (C. and G. 1912.)

85. Sketch the apparatus you would employ to determine the internal resistance of a Bunsen cell, and explain how you would make the determination. (C. and G. 1911.)

86. Describe a method of measuring the internal resistance of a battery of accumulators. (C. and G. 1912.)

87. Describe some form of direct-reading instrument for measuring insulation resistance and explain its principle of operation. (C. and G. 1913.)

(See also Nos. 32, 33, 34 on pages 27, 28.)

CHAPTER VII

THE POTENTIOMETER

The potentiometer is *the* electrical engineering measuring instrument *par excellence.* There are few kinds of electrical measurements to which it cannot be adapted and there are several which it accomplishes with an ease and accuracy that render it practically indispensable.

As its name implies, the potentiometer works by means of potential indications or rather by " balancing " potentials. It is in fact the present day descendant of the appliances used in earlier times for the comparison of the electromotive forces of cells. In by-gone days when currents of electricity were mainly obtained from batteries of primary* cells which continually required renewal of the chemicals, when there were no generally accepted standards of electromotive force (or current) and electromotive forces had to be specified in terms of the number and kind of cells used and a satisfactory standard cell was still being hunted for, it was a matter of frequent necessity to determine experimentally the ratios of the electromotive forces of cells.

In these days comparison of E.M.F.'s of cells is not of practical importance but the development of the processes for conducting

* Primary cells produce currents of electricity direct from chemical action and are designated as " primary " to distinguish them from storage cells which sometimes also go by the name of " secondary " cells. Still another name for them is " accumulators." (Storage cells merely give out more or less of the electricity put into them in the process of " charging " them.) In old text-books one will find descriptions of many types of primary cells, *e.g.* the bichromate, Bunsen, Grove, Smee, Minotto, Daniell, Niaudet, Leclanché. Dynamos and storage cells have supplanted primary cells for almost every purpose. The only important cases of the modern use of primary cells are : (1) the Weston Normal Cell which is used as a portable standard of E.M.F., (2) the Leclanché cell and its modifications in the form of " dry " cells which are still the handiest for working electric bells, etc.

such measurements has provided us with the modern potentiometer, an appliance of unrivalled practical utility. A short sketch of the various methods of comparing the E.M.F.'s of cells will be of more than historical interest as the repetition of such experiments provides the student with practice in the manipulation of electrical apparatus without resorting to the too monotonous repetition of stock experiments.

Comparison of E.M.F.*'s of Cells.*

The method of comparing the E.M.F.'s of two cells that would first occur to the minds of the majority of people not having a suitable voltmeter is that of connecting one of the cells in series with a resistance and galvanometer as shown in Fig. 80, noting the

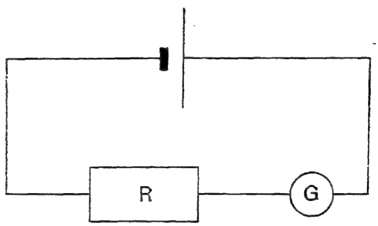


Fig. 80.

deflection produced in the galvanometer and then repeating the process with the other cell, using the same resistance. Then, acting on the assumption that the resistance in the two cases was the same and the currents produced were proportional to the deflections, the ratio of the E.M.F.'s would be taken to be that of the respective deflections. This method goes by the name of the *method of equal resistances.* It is to be noted that the resistance used should be as great as possible to prevent the condition of the cell being altered through being called upon to supply any considerable amount of current.

It will be observed, however, that the internal resistance of the cell is included in the circuit in each case and it will be a very rare accident that the internal resistances of the cells used are exactly alike. To eliminate the resistances of the cells themselves, the *sum and difference method* was devised. This consists in

connecting both cells in the circuit (1) so as to send their currents in the same direction, (2) so as to oppose each other. Fig. 81 shows the diagrams of connections in this case. There is no doubt about the resistances in circuit being the same in these two cases and the currents will be proportional respectively to the sum and difference of the E.M.F.'s of the cells. Hence the ratio of the E.M.F.'s of the cells is taken as the ratio of the sum to the difference of the deflections obtained.

The methods already described require a calibrated galvanometer for accurate results; otherwise, errors may be made in assuming the currents to be proportional to the deflections observed.

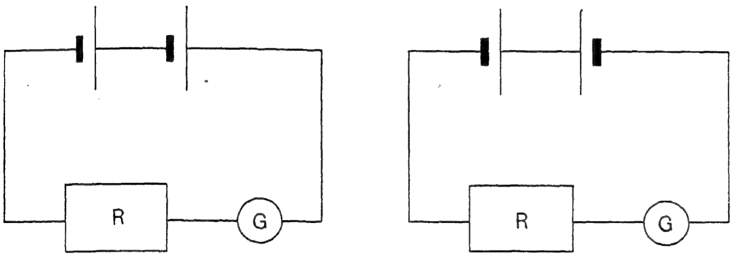


Fig. 81.

The *method of equal deflections* was devised to dispense with the necessity for knowing how the galvanometer deflection varied with the current. This was of some advantage in the days of old fashioned galvanometers*. The method consisted in connecting the cells in turn as indicated in Fig. 80, but the resistance was adjusted so as to give the same galvanometer deflection in each case and the ratio of the E.M.F.'s was taken as the ratio of the respective resistances (including the resistance of the galvanometer). This does not eliminate the internal resistances of the cells, but Wheatstone's modification of the method meets this difficulty (and also eliminates the resistance of the galvanometer).

* The student repeating these experiments will almost of necessity have to employ more or less modern apparatus, such as a resistance box for providing known resistances and either a mirror galvanometer or some form of sensitive portable ammeter for indicating the current.

Wheatstone's method consists in choosing two deflections (one about half of the other) and adjusting the resistance in the case of each cell to produce first one and then the other of these deflections. The ratio of the E.M.F.'s is then ascertained from the ratio of the respective *changes* in the resistance required to produce the change in the deflection.

The effect of inevitable "errors of observation and experiment" is seriously increased in methods depending upon the ratio of the differences of observed quantities, and it is quite possible for Wheatstone's method to yield results inferior to those of the simpler methods previously described. The greater the resistance used, the smaller the error caused by ignoring the internal resistance of the cell.

As a matter of fact it is not necessary to arrange for either equal resistances or equal deflections if the ratio of the E.M.F.'s is taken to be that of the respective products of resistance and deflection. This procedure goes by the name of the method of *unequal resistances and deflections.*

The methods enumerated so far may be all described as "direct deflection methods." The methods remaining to be dealt with are all "compensation methods" or null methods and have all the advantages referred to in another connection on page 104, viz.: that, as the galvanometer is only used to indicate the presence or absence of a current in it, the sensitiveness of the galvanometer may be increased so as to increase the refinement of the determination; the galvanometer does not need calibration and its resistance does not affect the result; the accuracy of the determination is not limited by the length of the galvanometer scale and greater resistances may be employed.

Fig. 82 gives the diagram of connections for Bosscha's compensation method (sometimes also called Lumsden's method)*. It will be seen from Fig. 82 that the galvanometer has applied to it two opposite E.M.F.'s. Suppose that the resistances R', R'', are so arranged that there is no deflection in the galvanometer, it follows that the differences of potential between the galvanometer terminals due to each coil are equal and opposite; but the pro-

* The student who will not be carrying out the actual experiment may omit Bosscha's method.

portions that these bear to the E.M.F.'s of the cells are directly as the resistances in series with the cells, so that we have

$$\frac{E'}{E''} = \frac{R' + x'}{R'' + x''},$$

where x' and x'' are the unknown resistances of the cells compared. If R' and R'' were large enough to make x' and x'' negligible, we could take $E' = E'' \times \frac{R'}{R''}$. In any case x' and x'' can be eliminated thus. Find another pair of values of the resistances r' and r'' for which there is no deflection in the galvanometer. Then

$$\frac{E'}{E''} = \frac{r' + x'}{r'' + x''},$$

so that finally we have

$$E' = E'' \times \frac{R' - r'}{R'' - r''}.$$

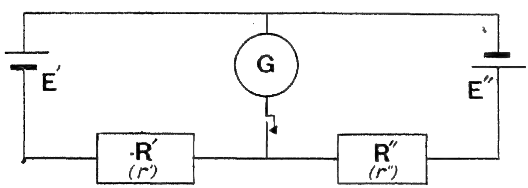


Fig. 82.

Apart from the advantage of being a null method, Bosscha's method possesses no particular merit. As in Wheatstone's method, the elimination of the internal resistances of the cells is only accomplished by introducing into the calculations the ratio between two differences of resistances. This causes any experimental errors to have a disproportionately large effect on the result.

Poggendorff's Method.

All the methods remaining to be described are based on the same principle, in fact, they are all modified or developed forms of the method originally devised by Poggendorff *. The same principle is also applied in the modern potentiometer. The names

* See Poggendorff's *Annalen*, Vol. 54, p. 161 (1841).

"Poggendorff's method" and "Potentiometer" will often be found applied to any of these methods.

The system of connections for Poggendorff's method is represented diagrammatically in Fig. 83. Let E' and E'' be the E.M.F.'s of the cells which are being compared, and let them be connected up to the resistances MP and PN in the manner shown in Fig. 83. The cell with the greater E.M.F. is to be at E''.

It is obvious that in the circuit of E' in which the galvanometer is placed, there is opposed to E' the difference of potential between M and P due to the cell E''. It is possible to adjust the resistances MP and PN to be such that these opposing E.M.F.'s are equal in magnitude, and when this is done there will be no

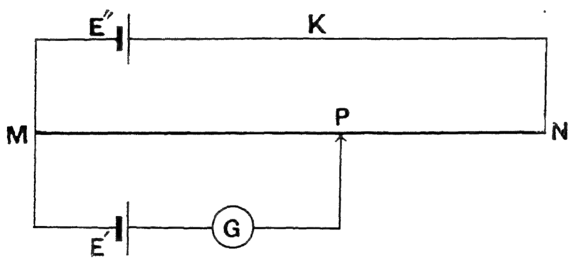


Fig. 83.

current in the circuit of E', and therefore there will be no deflection produced in the galvanometer (and "balance" is said to be obtained).

When this adjustment has been carried out, the difference of potential between M and P is equal to E'. But the ratio of this to E'' is the same as the ratio of the resistance of MP to the total resistance in the circuit of E''. Hence, if R' be the resistance of MP, R'' the resistance of MN (that is $MP + PN$) and x'' the (unknown) internal resistance of the cell E'', we at once arrive at the relation $\dfrac{E'}{E''} = \dfrac{R'}{R'' + x''}$.

Poggendorff neglected the resistance of the cell (x''). To minimise the error so introduced, it is necessary to arrange to have R'' very large.

In the ordinary way one would require two resistance boxes for Poggendorff's method—one for MP, the other for PN, but it can

be done with a single Wheatstone Bridge resistance box using the ratio coils to provide the resistance *PN* and the adjustable arm for *MP*. Fig. 84 gives the diagram of connections for this use of the Wheatstone Bridge box, in a form convenient to follow. It is important to guard against connecting up the cell before seeing that adequate resistance is provided in the box; it would short-circuit the cell to connect it up to a resistance box with all its plugs in *. It is also necessary to take care that the positive terminals of both cells (or the negatives of both cells) are connected to the point *M*. Unless this is done the cells will not be opposing in the galvanometer and no balance will be obtainable.

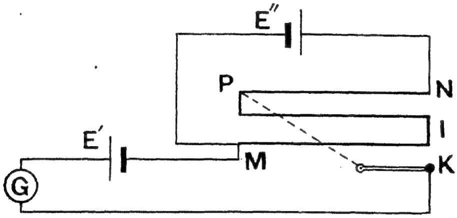


Fig. 84.

It is possible to eliminate the effect of the internal resistance of the cell in Poggendorff's method in a similar manner to that explained for Bosscha's method and open to the same objections. Thus, if we obtain another set of values of the resistances *MP* and *MN* which give balance, say r' and r'', we have

$$\frac{E'}{E''} = \frac{r'}{(r'' + x'')}$$

in addition to

$$\frac{E'}{E''} = \frac{R'}{(R'' + x'')}.$$

Eliminating x'' between these equations gives

$$\frac{E'}{E''} = \frac{R' - r'}{R'' - r''}\dagger.$$

* The Infinity Plug (I in Fig. 84) may be conveniently used as a switch.

† It may also be pointed out here that by eliminating E'/E'', we get an equation giving the value of x'', viz.

$$x'' = \frac{R''r' - R'r''}{R' - r'}.$$

It is obvious that this might be applied as a method of finding the internal resistance of a cell. This is substantially the method devised by Beetz. There is no particular virtue in it.

Du Bois Reymond devised a method of comparing the E.M.F.'s of cells but his method is nothing more nor less than Poggendorff's method, pure and simple. All that Du Bois Reymond did was to devise a particular form of apparatus for carrying it out. For the resistances represented by MN in Fig. 83 he used a stretched wire and adjusted for balance by sliding the point P along the wire. (Of course Fig. 83 is the diagram of connections for Du Bois Reymond's apparatus also.)

With this apparatus, if the wire is absolutely uniform and the *internal resistance of the cell E'' is negligible*, the ratio of the E.M.F.'s of the cells will obviously be the ratio of the lengths of wire in MP and MN when balance has been obtained.

One can quite understand the attraction that this form of apparatus would have for experimenters at a time when resistance boxes could not be made so accurately and cheaply as they are turned out now, but it is not so satisfactory as it might seem at first sight. Any practicable size of wire would have so small a resistance that the internal resistance of cell E'' would as a general rule be of the same order of magnitude, and its neglect would make the results obtained quite valueless. To attempt to correct for the internal resistance of the cell would, of course, cause so much trouble that it would be simpler to abandon the method altogether. There are other troubles connected with the use of a stretched wire for a resistance but what has already been said condemns it absolutely for comparing E.M.F.'s in the manner devised by Poggendorff.

However, Poggendorff's method can be so modified as to eliminate the error arising from internal resistance, whether a stretched wire resistance is used or not. The method of doing so was published independently by Pellat and Latimer Clark, but as the latter was the only one of the two to use it, the method goes by his name.

Latimer Clark's Method.

The great merit of this method of comparing E.M.F.'s is that it makes no demand for current from the cells compared and avoids entirely errors arising from their internal resistances. This is done by using Poggendorff's method, not to compare the cells directly, but to compare each of them in turn with a third cell

(or battery of cells). The procedure will be fairly obvious from the diagram of connections given in Fig. 85. Ignoring the cell E'' in the meantime, it is clear that Fig. 85 shows the connections for comparing cell E' against cell E in the manner shown in Fig. 83. Let P be the point of "balance" in this case, and we have

$$\frac{E'}{E} = \frac{\text{resistance of } MP}{\text{resistance of } MN + x},$$

where x is the (unknown) internal resistance of cell E.

Now let us substitute cell E'' for cell E' or—what comes to the same thing—disconnect cell E' by the key S and connect in

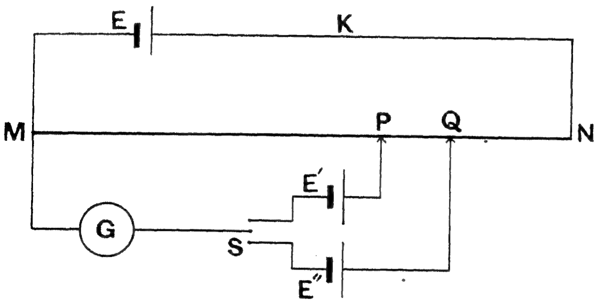


Fig. 85.

cell E'', and balance once more. Suppose that the point of "balance" is now at Q; we then have

$$\frac{E''}{E} = \frac{\text{resistance of } MQ}{\text{resistance of } MN + x}.$$

From these two equations we at once derive the result

$$\frac{E'}{E''} = \frac{\text{resistance of } MP}{\text{resistance of } MQ}.$$

If a uniform stretched wire is used for resistance MN, the above ratio (E'/E'') is simply that of the lengths of wire in MP and MQ.

This equation for E'/E'' is obviously correct provided that the E.M.F. of cell E and the resistance in its circuit is the same on both occasions (that is (1) on balancing E' against E, (2) on balancing E'' against E). This will generally be the case if these two operations are performed one immediately after the other, *unless the cell E is being run down during the experiment*. This may be checked

by repeating the determination of the point of balance with the cell first used. (Note that cells E' and E'' are not called upon to supply any current beyond the minute amounts producing the deflections in the galvanometer that may occur in the process of finding the exact point of balance.)

In devising apparatus for this method the chief point to be aimed at is to keep the difference of potential between M and N (Fig. 85) steady throughout the experiment. The causes which alter it are the changes of E.M.F. and internal resistance of E, and the changes of resistance of MN, due to the chemical and heating effects of the current in the circuit. These disturbances can be kept small by using a high resistance for MN. They can also be reduced by choosing for E a type of cell which has a small rate of fall of E.M.F. with current and a small internal resistance; the storage cell meets these requirements better than any other type. A further improvement is to have the resistance MN constructed of a material having a small temperature coefficient of resistance.

Latimer Clark preferred the use of a length of wire for MN to the use of resistance boxes. His object was to produce a good "workshop method" and the simpler manipulation and easier calculations involved in the use of a plain wire settled his choice of that form of the apparatus. However, a sufficiently large resistance for MN could not be obtained by a single stretched wire of any practicable length, so he used a wire in the form of a spiral wound in a groove cut in a wooden cylinder about 1 metre long and 10 cm. in diameter. The cylinder was mounted on bearings leaving it free to rotate, an electrical contact at M and N was established by means of amalgamated copper discs running in suitable mercury troughs.

To this apparatus Latimer Clark gave the name of "potentiometer"; this name was retained by Crompton for the very beautiful piece of modern apparatus by which he perfected the practical application of the principle of Latimer Clark's method.

The use of resistance boxes with the foregoing method is associated with the name of Lord Rayleigh who applied it in the comparison of standard cells. The theory of his method is precisely the same as for Latimer Clark's, the only difference being in the form of the apparatus. Two resistance boxes are used, one

for MP, the other for PN, and adjustment for balance is made by taking resistance out of the one and putting it into the other. The sum of the resistances in the boxes should be kept constant and at a high amount such as 10 000 ohms.

Fig. 86 gives the diagram of connections in a form immediately applicable.

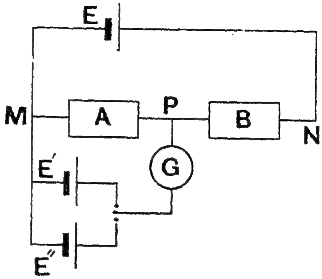


Fig. 86.

To keep the deflections from being too large during the initial adjustment for balance, Rayleigh used a resistance in series with the galvanometer instead of shunting it. This had the advantage of preventing the cell E' or E'' from giving out anything more than an insignificant current under any circumstances.

Although Latimer Clark's form of apparatus has been superseded by the modern potentiometer, something like it is used in all laboratories for instructional experiments preliminary to the use of the modern (and to the beginner rather complicated-looking) instrument. Generally a metre wire "bridge" is used, and one with several folds of wire is to be preferred to a single wire *.

The following hints will assist the student in the difficulties usually met with when this experiment is performed for the first time. After connections have been made and you are ready to find out at what part of the wire the point of balance (P) is, start with the galvanometer at its least sensitive shunt so that the deflections have a good chance of being on the scale. If the deflection is to the same side for all positions of P along the wire, examine the connections; either the poles of one of the cells want interchanging or cell E' has greater E.M.F. than cell E. The latter will not be the case if E is a storage cell unless it happens to be out of order. The former is of common occurrence; in fact,

* The chief practical difficulties associated with the use of short lengths (such as 1 metre) of wire for this experiment arise from (1) the running down of the battery E owing to the large current sent through a small resistance, (2) the fluctuation of the wire resistance from the heating effects of the large currents through it, (3) the sag of the wire owing to thermal expansion.

it is a frequent mistake to connect the cells in wrongly in this experiment, and the student must take great care to be sure he has the cells connected in with the poles as indicated in the diagram *.

Potentiometer.

To Fleming † belongs the honour of discovering the possibilities of the application of the above principle to general electrical measurements. The essential differences between the modern potentiometer and that of Latimer Clark will be fairly well understood on reference to Fig. 87 which gives a skeleton diagram of the potentiometer connections. (Since the production of the original Crompton-Fisher potentiometer, others have added devices for extending its utility.)

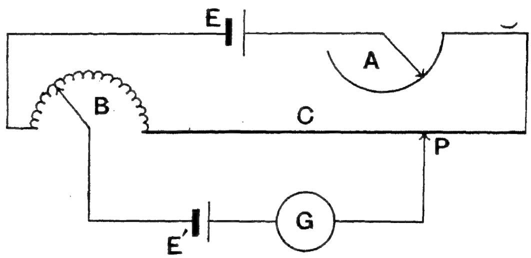


Fig. 87.

The resistance in the circuit of E consists of a fine adjustable resistance (A), a set of coils (B), and a stretched wire (C) with a scale attached marking it off into 1000 or more divisions. The coils constituting B are each made of the same resistance as 1000 divisions of the wire C.

The apparatus is first used with a standard cell at E', and the contact maker at B is set so as to include in the circuit of E' the number of coils given by the first two significant figures of the

* The terminals of standard cells are always marked, the positive terminal being indicated by a plus (+) and the negative by a minus (−). Storage cells have either their terminals so marked or the positive terminal is painted red and the negative terminal black. In primary cells the terminal connected to the zinc rod or plate is the negative one; the other terminal (connected to the carbon or whatever the other electrode may be) is the positive.

† See *Industries*, July and August, 1886.

E.M.F. of the cell (10 in the case of the Weston Normal Cell), while the contact maker at P is set to the number of divisions on the wire given by the remaining figures of the E.M.F. of the cell (183 in the case of the Weston Normal Cell). Balance is then obtained by adjusting the resistance A. In this way the circuit is arranged so that the E.M.F. of E' can be read off directly from the numbers at which B and C are set.

The E.M.F. of any other cell (say E'') is found by connecting it up in a similar manner to E' and adjusting B and C only until balance is obtained. Its E.M.F. can then be read off from the numbers at which B and C have to be set to obtain balance.

It will then be seen that the potentiometer gets rid of all calculations, and thus goes one better than Latimer Clark's apparatus, while effecting improvements as regards the amount of resistance in the circuits without using a cumbrous wire arrangement.

So far, reference has been made only to the comparison of E.M.F.'s of cells but the later methods given can be easily applied to differences of potential, however produced. The adaptation to other kinds of measurement will be dealt with presently.

Potentiometer Apparatus.

Until recently potentiometers were rather expensive instruments and in educational institutions instruction in their use was generally limited to a degree that was not in keeping with their practical importance. Potentiometers are now manufactured at much lower prices than formerly but we have also the advantage of now being able to obtain cheap forms of potentiometer which serve as a sort of intermediate step between the simple slide wire referred to on page 147 and the more elaborate instruments used for the best class of work.

Fig. 88 shows the arrangement of an instructional potentiometer made by Gambrell Bros. at the moderate price of £6. The design of this instrument allows all the various parts and their connections to be seen from the outside. The coils B and slide wire C are made of a continuous length of 16 feet of bare manganin wire connected to plug terminals at appropriate intervals. The

resistance of the wire between each of the terminals of B is adjusted to be equal to that of 100 scale divisions of the slide wire C. The adjustable resistance A (called the rheostat) is provided by a turn of wire on a revolving disc, the rotation of which admits of any required length of it being cut out of the circuit. In addition there are also two small coils one or other or both of which may be included in the circuit when sufficient resistance cannot be obtained from the wire on the disc alone.

The apparatus is used in the following manner. One storage cell is connected up between the terminals marked ACC. A

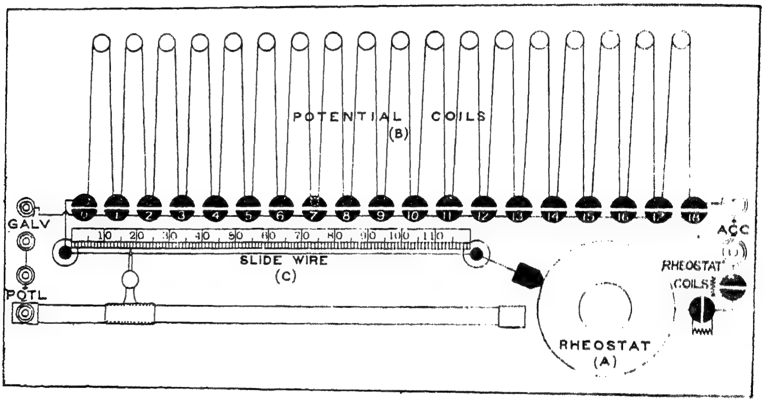


Fig. 88. Gambrell Instructional Potentiometer.

sufficiently sensitive galvanometer or micro-ammeter is connected between the terminals marked $GALV$ and a Weston Normal Cell is connected between the terminals marked $POTL$. The slider regulating the point of contact on the slide wire C is set at 18.3 divisions and a plug is inserted at No. 10 terminal of the coils B. The rheostat is then adjusted till there is no deflection in the galvanometer. After this the Weston Normal Cell is disconnected and its place is taken by the potential to be measured *.

The potential is measured by setting the slide wire slider at 60 divisions, shifting the plug to the terminal of B which gives

* It is important to leave the adjustment of the rheostat A undisturbed during the subsequent measurements. When carrying out prolonged tests it is advisable to check the adjustment with a Weston Normal Cell at intervals.

the smallest deflection in the galvanometer and the adjustment for no galvanometer deflection is completed by moving the slider along the slide wire C. The E.M.F. of the potential measured is read off as follows: the number of the terminal B on which the plug is placed indicates the number of tenths of a volt; the number of slide wire divisions indicates the number of thousandths of a volt.

The accuracy of this potentiometer is only limited by the power of estimating fractions of a division on the slide wire. In the middle of its range it can give results accurate to 1 part in a 1000 without working to fractions of a scale division, so that it can be used for work of considerable accuracy.

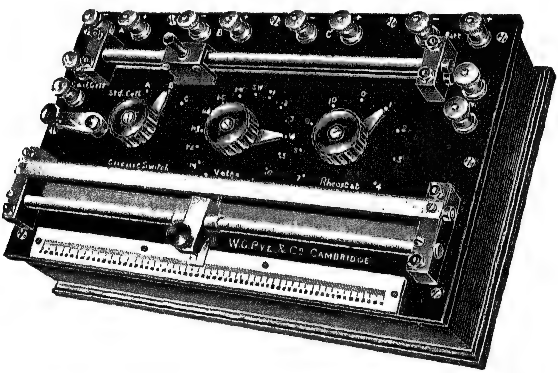
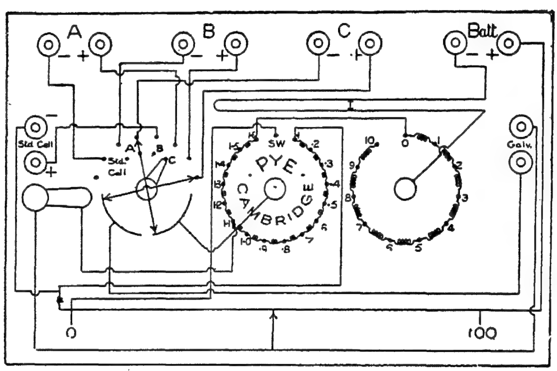


Fig. 89. Pye's Granta Minor Potentiometer.

The more elaborate forms of apparatus are used in a similar manner. In all of these the adjustable resistance A will be found in two sections, viz., (1) a set of coils called the rheostat coils by means of which the first rough adjustment of A is made with the Weston Cell connected in, (2) a low resistance wire rheostat for finishing the exact adjustment of A. As a rule, they also have a distinct pair of terminals for the Weston Normal Cell.

Fig. 89 illustrates Pye's "Granta Minor" Potentiometer which is capable of performing all ordinary potentiometer work with great accuracy and is produced at the price of only £9. 10*s*. In this instrument the rheostat consists of 10 coils for rough adjustment of balance with the standard cell and a straight

rheostat wire for the fine adjustment. Connections are made to appropriate points of the potential coils for balance with the Weston Normal Cell which can thus be performed by turning the circuit switch (shown on the left of the illustration) to the *Std Cell* position without reference to the position of the contact maker on the potential slide wire. Of the six pairs of terminals shown in the illustration, one pair is for the Weston Normal Cell, one pair (marked *Batt*) for the accumulator, one pair for the galvanometer and three pairs are available for potentials undergoing measurement. The complete arrangement of connections is shown in Fig. 90.



POTENTIOMETER N° 7554.

Fig 90.

The slide wire is calibrated for uniformity and the potential coils are adjusted to 1 part in 1000, so that the instrument is capable of accuracy to within from 1 part in 1000 to less than 1 part in 10 000 according to the circumstances of the measurement.

A form of Granta Minor Potentiometer is also made for measuring very small potentials such as the E.M.F. of a thermo-couple, at a cost of £10.

Fig. 91 is an illustration of Tinsley's Students' Potentiometer, which is an instrument of precision although, as its name implies, it is not so elaborate as the Universal Potentiometer by the same

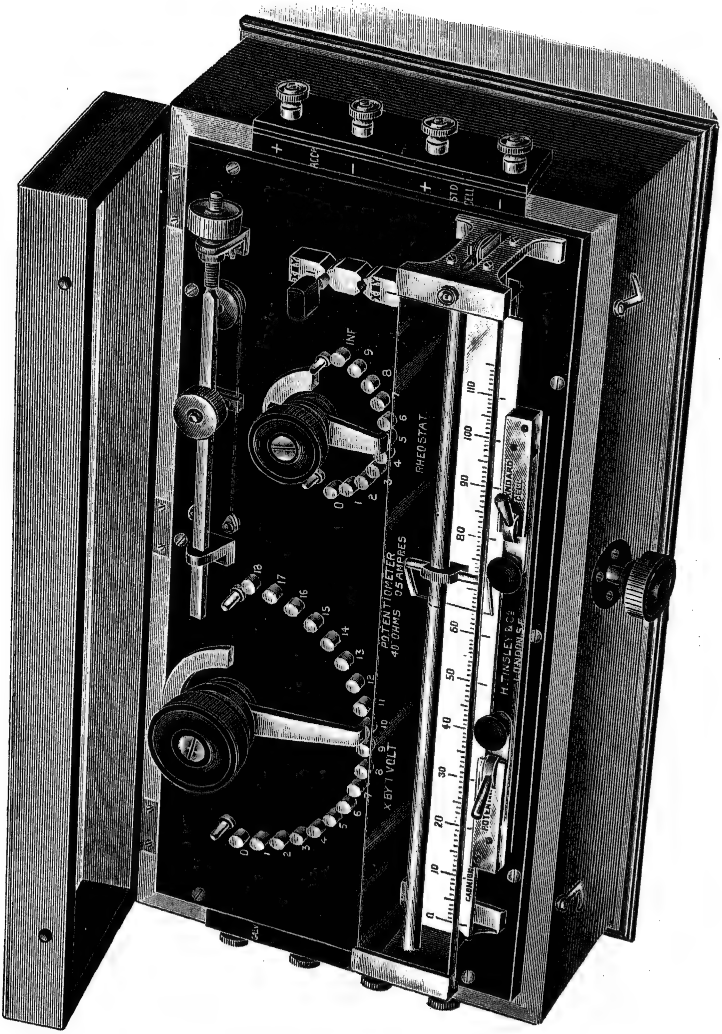


Fig. 91. Tinsley's Students' Potentiometer

maker. Tapper keys are provided both for the Standard Cell * and the potential difference. The adjustment of the contact position on the slide wire (C) is made by a handle projecting from the front of the box which works a system of cords and pulleys. The fine adjustment of the rheostat is made by working a milled head screw. The rheostat coils are provided with an "infinity" stud which enables the circuit of the storage cell to be broken without disconnecting it. In using this instrument the procedure is the same as that already detailed, the only differences being in the manipulation of the apparatus.

A plug, shown at the right-hand side of Fig. 91, enables a system of shunts to be connected in (after adjustment with the Standard Cell) which reduces the whole of the potential values indicated to one-tenth of their nominal amounts. This enables the instrument to be used for measuring potentials under one volt with greater accuracy.

Multi-range Potentiometers.

Many modern potentiometers are provided with shunt devices for making the instrument capable of measuring potentials one-tenth, one-hundredth or some decimal sub-multiple of the normal amount for the unshunted potentiometer. These are called multi-range potentiometers. The arrangement adopted to effect this result will be understood on reference to Fig. 92 which is a reproduction of the diagram given in Fig. 87 with the addition of the resistances for effecting the change of range. For the adjustment of balance with the standard cell, the range switch has to be set at the position which leaves the potentiometer in the ordinary state. In subsequent potential measurements the range of the potential coils can be reduced to one-tenth by setting the range switch at the position which shunts the potential coils B and C by putting the resistance S in parallel with them and also throws the resistance R into the accumulator circuit. The amounts of R and S are so

* The following signs are generally used in potentiometer apparatus to indicate the respective terminals :

Cd or Std cell		..	..	Weston normal cell.
Acc	..	..	..	Storage cell.
Galv	..	..	..	Galvanometer.
Pot	..	..	..	Potential difference, to be measured.

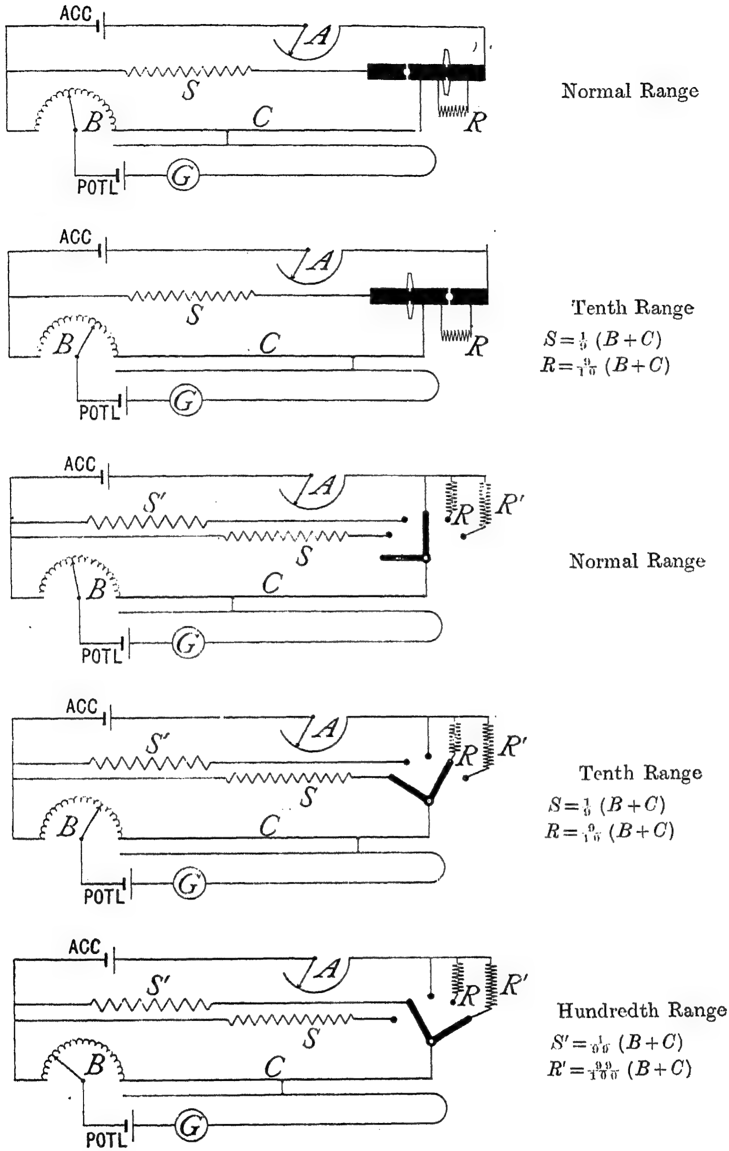


Fig. 92. Diagrams of Multi-Range Potentiometers.

arranged as to make the resistance in the accumulator circuit the same as before while the fall of potential over B and C is one-tenth of what it was, that is

$$R = \frac{9}{10}(B + C), \qquad S = \frac{1}{9}(B + C).$$

To reduce the range to one-hundredth the range switch is turned to the position which brings in resistances R' and S' to perform similar functions as the R and S already referred to, but in this case $$R' = \frac{99}{100}(B + C) \text{ and } S' = \frac{1}{99}(B + C).$$
(The plug switch arrangement cannot give more than two ranges with the use of only one plug.)

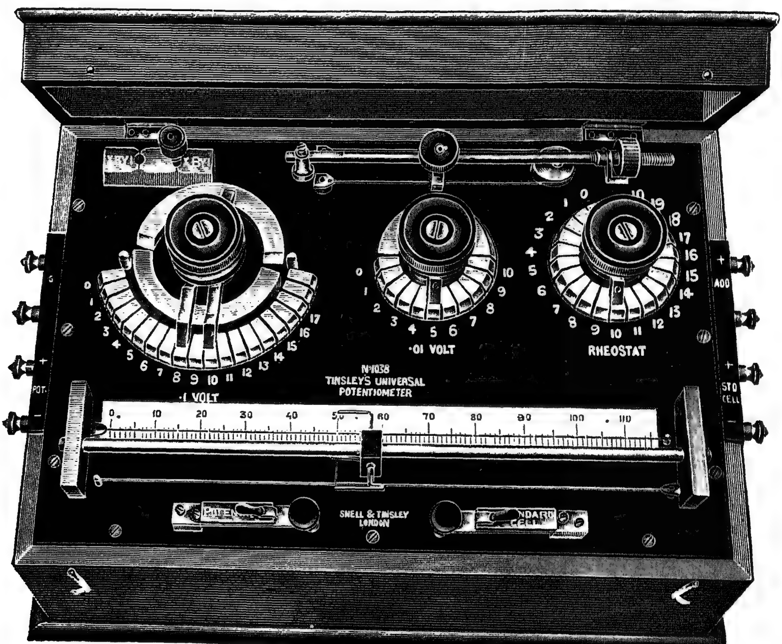


Fig. 93.

Tinsley's Universal Potentiometer.

The principal features of this precision potentiometer may be gathered from the illustration in Fig. 93. In addition to the ordinary potential coils the dial of which is seen on the left in the

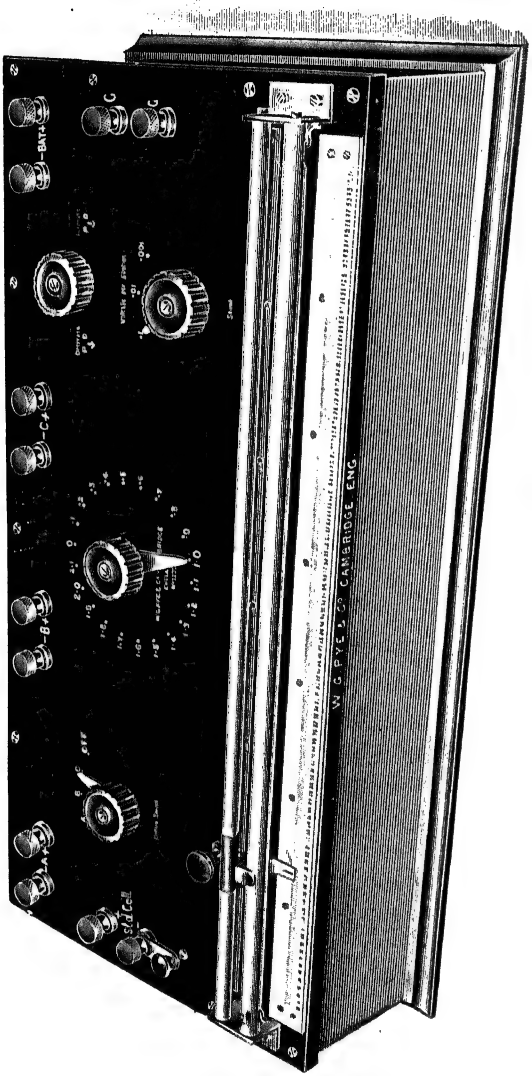


Fig. 94.

illustration, there is another set belonging to the vernier dial seen in the centre of the illustration which are connected across the prongs of the main dial on the left; these vernier coils give the next decimal place after the main coils and the slide wire is only required to give the figures for the further decimal places. This arrangement allows for direct reading being carried one decimal place further than the ordinary arrangement.

The Tinsley potentiometer is a two-range instrument, the range of the whole instrument being capable of being reduced to one-tenth by the plug on the top left-hand corner. (The vernier arrangement dispenses with any necessity for providing for further reductions of range.) For a precision instrument of the finest scientific construction it is wonderfully compact, measuring only 18 inches in length overall.

This instrument also forms the central piece of Tinsley's Alternating Current Potentiometer, an apparatus with many interesting features which it is beyond the scope of this work to detail: we only mention its existence here on account of its interest as showing a rather unexpected development of potentiometer methods of working.

Pye's Granta Potentiometer.

A number of forms of precision potentiometers are made by W. G. Pye and Co. but in their main features they are all similar to the one illustrated in Fig. 94, the differences being confined to matters connected with the range of the instrument. Fig. 94 shows their multi-range potentiometer having three ranges. The manner of handling these instruments is practically identical with that of the Granta Minor Potentiometer already described but they are adjusted with much greater refinement and are in other respects of superior construction for work of the highest degree of accuracy.

Paul's Long-Range Slide Potentiometer.

Fig. 95 illustrates Paul's Slide Potentiometer. In this instrument also connections to appropriate positions for the Weston Normal Cell are provided permanently in the inside of the coils and it is only necessary to depress the key shown at the left of the

illustration while adjusting the rheostat coils and wire for balance with the Weston Normal Cell. Five pairs of terminals are provided at the back of the instrument for connecting up any potential differences to be measured and the circuit switch at the left of the instrument enables these to be connected for measurement in turn without disturbing external arrangements.

Apart from these differences in manipulation, the instrument is used in the manner already described.

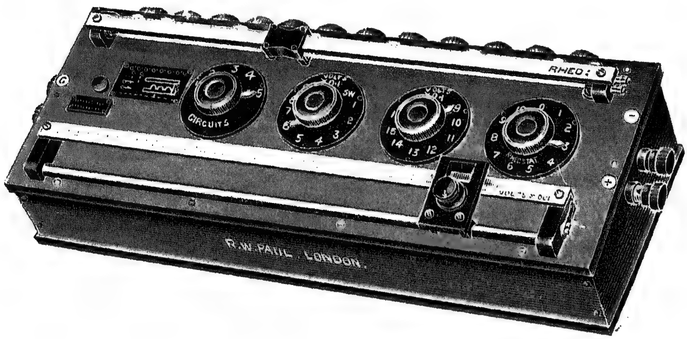


Fig. 95.

Standard Cells.

A great deal of work has been done with a view to producing a cell which would serve as a portable working standard of potential difference. The first good standard of this kind was produced by Latimer Clark and is known as the Clark Cell. Improvements in detail have been made on the Clark Cell by several experimenters, but the most important modification was made by Dr Weston who substituted Cadmium for Zinc as one of the electrodes, and so effective have been the alterations made by Dr Weston that his form of cell is practically a new standard and it is now universally adopted for this purpose under the title of the Weston Normal Cell. The nature of the action of cells is dealt with in Chapter VIII but we may explain here that standard cells are now generally mounted in a special manner. Fig. 97 shows, *inter alia*, the form of internal construction now usually adopted and Fig. 96 illustrates a common form of the external case.

The International Electrotechnical Commission have assigned the value of 1.0183 International Volts as the electromotive force of the Weston Normal Cell at 20° C. and its electromotive force

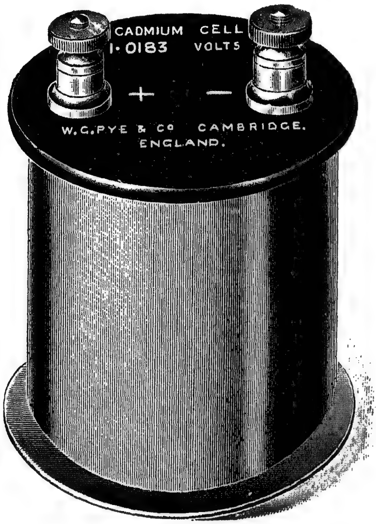


Fig. 96. Weston Normal Cell.

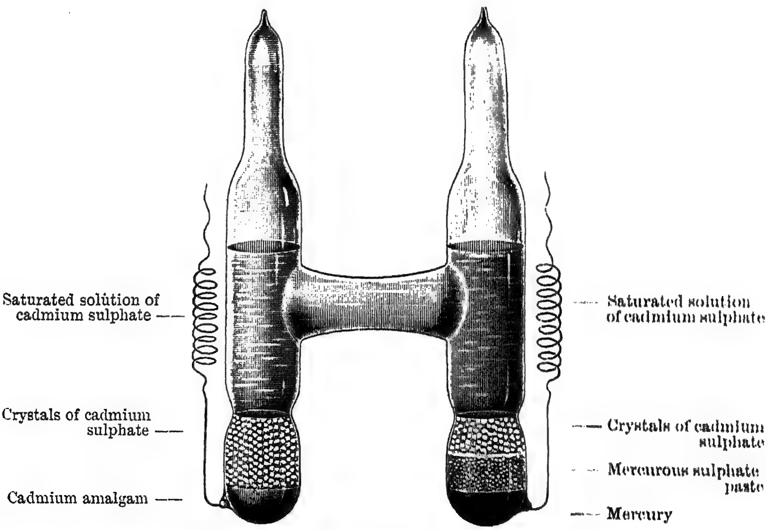


Fig. 97. Interior of the Weston Normal Cell.

at other temperatures (between 0° C. and 40° C.) as being given by the formula

$$E_t = E_{20} - .000\,040\,6\,(t-20) - .000\,000\,95\,(t-20)^2 + .000\,000\,01\,(t-20)^3.$$

As the change of E.M.F. of the Weston Normal Cell is only about .000 04 volt per Centigrade degree, it is not always necessary to make allowance for temperature corrections. The following list is compiled from the formula given.

Temperature in degrees Centigrade	E.M.F. of Weston normal cell
10	1.0186
14.3	1.0185
17.3	1.0184
20	1.0183
22.4	1.0182
24.4	1.0181
26.4	1.0180

As the Clark Cell was at one time extensively used it may be of interest to give the following particulars respecting its E.M.F. At one time the E.M.F. of the Clark Cell was taken as 1.434 volts at 15° C., its E.M.F. being calculated in accordance with the formula

E.M.F. of Clark Cell $= 1.434 - .0011\,(t-15)$ (old formula).

It is now known that this value is in error and the Clark Cell has an E.M.F. of 1.4326 International Volts at 15° C. A number of *Clark Cells will be found with their voltage marked at the old figure* which is 1 too high in the third decimal place.

E.M.F. of Clark Cell $= 1.4326 - .0011\,(t-15)$ (correct formula).

The temperature correction for the E.M.F. of the Clark Cell is too great to be ignored in any circumstances. In this respect the Weston Normal Cell is much superior.

Another form of standard cell is the Hibbert Standard Cell which has an E.M.F. of precisely 1 volt.

The Weston Normal Cell is the nearest approach to perfection that has been attained up to the present time and should be used exclusively for accurate work. Nevertheless, it may be useful to use the other forms of standard cell for instructional purposes

—especially as potential differences to be measured—in the first experiments with a potentiometer; their use for this purpose has the further advantage that the accuracy of the determination can be readily checked.

Potentiometer Accessories.

The measurement of potential differences in general is accomplished as follows: the E.M.F. to be measured is applied to a suitable high resistance of which a suitable known portion is "tapped"—as shown in Fig. 98—for direct measurement of

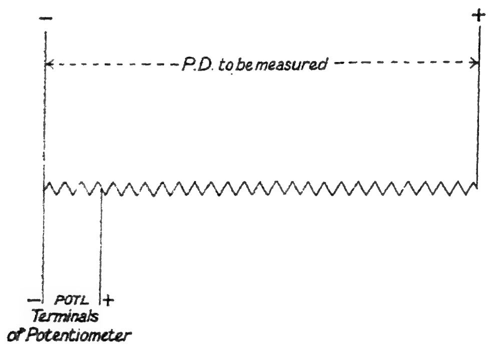


Fig. 98.

the corresponding fraction of the whole potential difference. The difference of potential measured directly by the potentiometer has to be multiplied by the ratio of the whole resistance to the part between the potentiometer connections, in order to obtain the required E.M.F. which is applied to the whole resistance.

For such measurements it is usual to employ what is called a volt box. Fig. 99 illustrates the usual form of volt box and it will be seen from the diagram there given that the plug switch with which the box is fitted enables the potential terminals of the potentiometer to be connected between two points representing one-tenth, one-hundredth or other simple fractions of the whole resistance according to the position of the plug.

It is important that the potentiometer should not be subjected to too great a difference of potential (more than 1.9 volts cannot be measured directly) and care has to be taken after

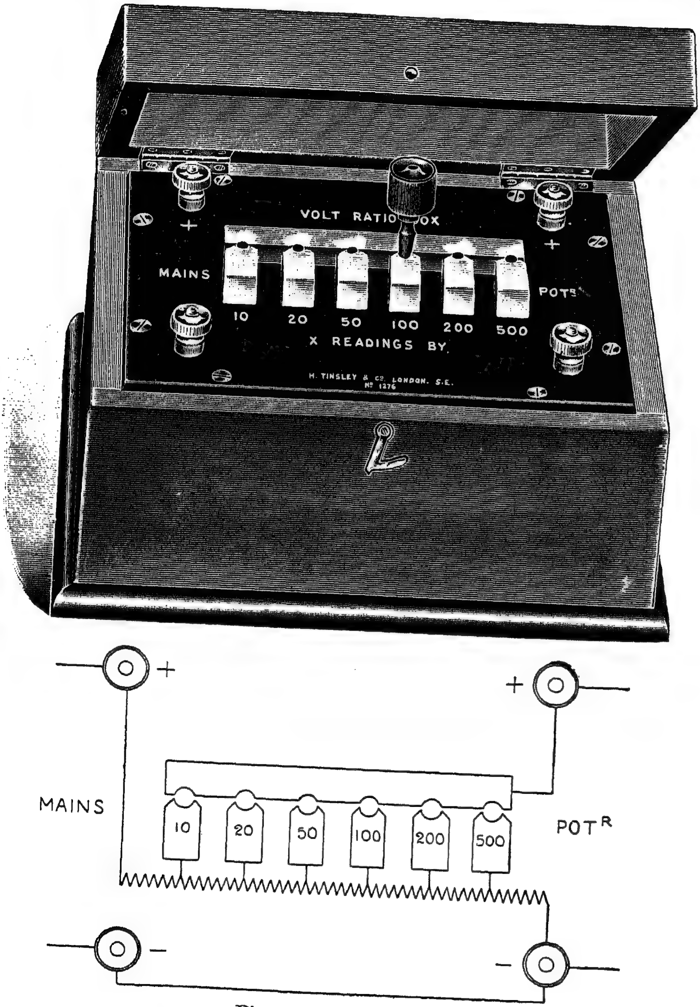
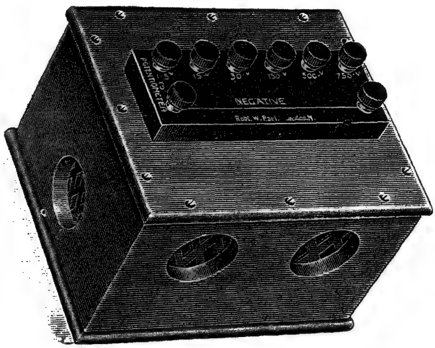


Fig. 99. Volt Box.

the box is connected up that the volt box plug is not inserted where it might do damage to the apparatus. Fig. 100 illustrates a form of volt box made by R. W. Paul in which the "ratio of

reduction" is appropriately set by connecting the positive terminal of the circuit supplying the E.M.F. to be measured to the appropriate binding screw on the box. This arrangement greatly reduces the chances of accidents.

An ordinary universal shunt box will generally be capable of being used as a volt box for E.M.F.'s up to 250 volts.



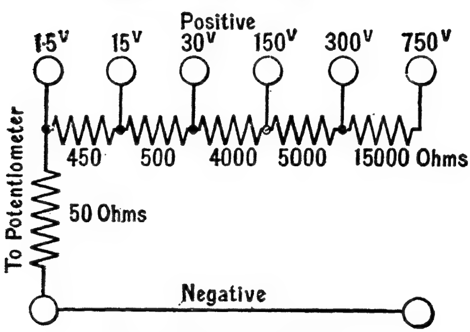


Fig. 100. Paul Volt Box.

Fig. 101 shows the arrangement for calibrating a voltmeter. All that is required in addition to what is indicated in Fig. 98 is to connect in the voltmeter and provide an arrangement for varying the E.M.F. over the range of the particular voltmeter tested.

For measuring currents by the potentiometer a known resistance is necessary, current being measured by means of the fall of potential over the resistance, as indicated in Fig. 102. Such a resistance must be capable of carrying the current to be measured

without suffering too great a rise of temperature and it is convenient that its resistance be a decimal sub-multiple of an ohm in order to avoid introducing calculations into the measurement. A one-ohm resistance is suitable for currents up to 1.5—1.8

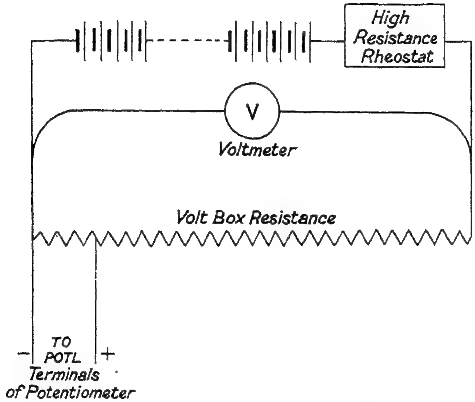


Fig. 101. Calibration of Voltmeter.

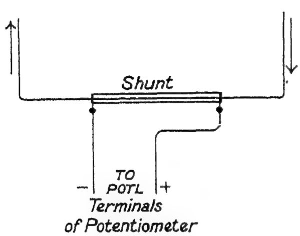


Fig. 102.

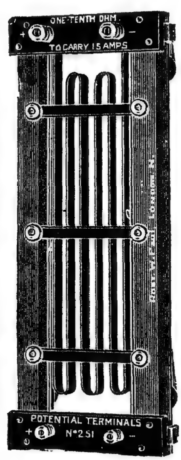


Fig. 103.

amperes, one-tenth ohm for currents up to 15—18 amperes, one-hundredth ohm for currents up to 150—180 amperes and so on. Standard shunts with an additional pair of terminals for the potentiometer connection are made for this purpose. See Fig. 103.

For instructional purposes, it may sometimes be possible to use an ammeter shunt.

Fig. 104 shows the diagram of connections for calibrating an ammeter. In this case it is necessary to make provision for varying the current over the range of the ammeter used.

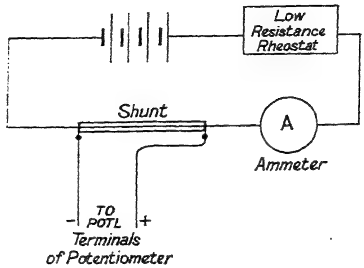


Fig. 104. Calibration of Ammeter.

It may be pointed out here that the power supplied to an electric circuit is proportional to the product of the electromotive force and current. When the electromotive force is stated in volts and the current in amperes their product measures the power in watts, the watt being the electrical unit of power. One horse-power is equivalent to 746 watts. The measurement of power by

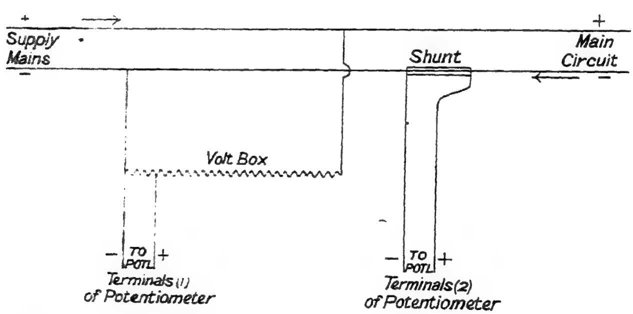


Fig. 105. Measurement of Wattage.

the potentiometer consists in the simultaneous measurement of the electromotive force and current or rather their measurement in close succession. The method of carrying out these measurements has been detailed above, but the complete diagram of connections is repeated in Fig. 105.

The potentiometer makes use of the fall of potential method for measuring resistance. In this case it is convenient for the known resistance to be one ohm or a decimal multiple or sub-multiple of an ohm and that particular multiple should be chosen which is nearest to the resistance to be measured. For this reason it is advisable to have a knowledge of the approximate amount of the unknown resistance. Fig. 106 gives a diagram of connections.

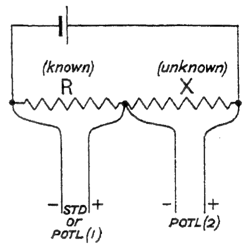


Fig. 106.

In the case of a measurement of resistance it is not necessary to use a standard cell but the amount of the current sent through the resistances should be such as to bring the differences of potential produced within the range of the potentiometer (about 1 volt). The rheostat of the potentiometer should be adjusted for balance with the potential coils (B) at 10 * and the slide wire at zero. If the range of the rheostat is not sufficient for this purpose the current through the known and unknown resistances should be changed accordingly. Balance is then to be arranged with the potential terminals of the potentiometer connected up to the unknown resistance by adjustment of B and C. From this the amount of the unknown resistance can be read off.

It may be pointed out that the instructional potentiometer shown in Fig. 88 may be used for measurements of E.M.F., current and resistance in the manner described.

MISCELLANEOUS QUESTIONS ON CHAPTER VII

88. You are given a length of German silver wire, a metre measure, a secondary cell, a sensitive galvanometer, connecting wire and a Daniell cell of which the electromotive force is known to be 1.08 volts. How would you proceed with this apparatus to measure the E.M.F. of a Leclanché cell? (C. and G. 1913.)

* If, as is usually the case, the known resistance is a decimal multiple or sub-multiple of an ohm. In any case, the potential coils and slide wire should be set to the amount indicated by the number of ohms in the known resistance

89. Explain, with sketches of connections, some form of direct reading potentiometer and show how it may be used to calibrate an ammeter. (C. and G. 1913.)

90. How would you calibrate an ammeter if the only standards at your disposal were a Clark cell and a low resistance ? Show in a diagram of connections the apparatus you would require, and describe how you would proceed. (C. and G. 1912.)

91. Describe some method by which the electromotive force of a cell can be very accurately determined. (C. and G. 1912.)

92. How would you proceed to calibrate an ammeter by a Crompton potentiometer and a standard cell ? Give sketches of connections and state what other apparatus is required. (C. and G. 1911.)

93. Describe the principle of the potentiometer. Make a neat sketch of the connections for measuring resistance, current, electromotive force and power by means of a potentiometer, standard cell and standard resistance. (C. and G. 1911.)

CHAPTER VIII

BATTERIES

The use of electric batteries leads us to the consideration of electro-chemical phenomena. Substances are regarded as combining chemically when they form some (new) substance with properties (*e.g.*, melting point, boiling point, density, conductivity, etc.) differing from any of the constitutents*. Chemical analysis has for its object the determination of the chemical composition of substances in terms of its constituents, but certain kinds of substance have been reached which have defied all attempts to split them up and these substances which have been found incapable of further analysis are called *elements* †. All substances are either elements, chemical compounds of two or more elements or mixtures of these.

It is found that the proportions of elements entering into chemical combination are always some multiple of a fixed ratio for each element, which is called the atomic weight of the element, since it represents a measure of the amount of the element in the ultimate unit or atom of its substance. In consequence of this, an ingenious shorthand system of representing the chemical composition of compounds has been devised; the atom of each element is represented by a letter of the alphabet (or pair of letters) and any compound is indicated by writing together the letters of

* There is a fundamental difference between a mere *mixture* and a chemical *compound*. When substances are merely mixed the constituent parts retain their individual properties and it is possible to separate them by physical means without necessarily employing chemical analysis. Frequently the heterogeneous structure of a mixture can be detected by a magnifying glass or microscope.

Substances may be mixed in any proportion but, as will be pointed out presently, chemical compounds are subject to a law of multiple proportions.

† This statement is subject to certain reservations with regard to radio-active elements.

the elements forming it with suffixes to indicate the number of the respective atoms combined. The formula so obtained represents the ultimate unit of the compound which is described as a molecule of it. Thus H_2SO_4 is the formula for Sulphuric Acid and indicates at a glance that it is composed of hydrogen, sulphur and oxygen in the proportions of

2×1.008	parts of hydrogen	(2.016)
1×32.07	parts of sulphur	(32.07)
4×16	parts of oxygen	(64)

to 98.09 parts of sulphuric acid.

The table on p. 171 gives a list of the known elements together with their symbols and atomic weights.

Electrolysis.

We are now in a position to explain the nature of the action which takes place when a current of electricity is sent through an electrolyte or solution. When a solution is made of a substance, the molecules of the substance are free to move in the liquid but, in addition, another effect takes place. A certain number of the molecules (according to the temperature and strength of solution) become dissociated into what are called *ions*. Thus in ordinary sulphuric acid which is a solution of H_2SO_4 in water, we not only have H_2SO_4 molecules but also H_2 ions and an equal number of SO_4 ions. It is the ions that are the effective agents in chemical action. Each ion is electrified; the H_2 ions in sulphuric acid have positive electricity (and hence they are called positive ions) and the SO_4 ions have negative electricity (and are called negative ions).

Suppose that we take a vessel containing sulphuric acid, dip into it two platinum plates some distance apart and prepare to send a current of electricity through the sulphuric acid by connecting the platinum plates to the terminals of a dynamo or battery as shown in Fig. 107. We may at once explain that the two platinum plates or electrodes are distinguished by separate names, the electrode which is connected to the positive terminal of the dynamo or battery (let us say it is a battery) is called the

Table of International Atomic Weights.

Element	Symbol	Atomic weight	Element	Symbol	Atomic weight
Aluminium	Al	27.1	Molybdenum	Mo	96.0
Antimony	Sb	120.2	Neodymium	Nd	144.3
Argon	A	39.88	Neon	Ne	20.2
Arsenic	As	74.96	Nickel	Ni	58.68
Barium	Ba	137.37	Niton (radium emanation)	Nt	222.4
Bismuth	Bi	208.0	Nitrogen	N	14.01
Boron	B	11.0	Osmium	Os	190.9
Bromine	Br	79.92	Oxygen	O	16.000
Cadmium	Cd	112.40	Palladium	Pd	106.7
Caesium	Cs	132.81	Phosphorus	P	31.04
Calcium	Ca	40.07	Platinum	Pt	195.2
Carbon	C	12.00	Potassium	K	39.10
Cerium	Ce	140.25	Praseodymium	Pr	140.6
Chlorine	Cl	35.46	Radium	Ra	226.4
Chromium	Cr	52.0	Rhodium	Rh	102.9
Cobalt	Co	58.97	Rubidium	Rb	85.45
Columbium	Cb	93.5	Ruthenium	Ru	101.7
Copper	Cu	63.57	Samarium	Sa	150.4
Dysprosium	Dy	162.5	Scandium	Sc	44.1
Erbium	Er	167.7	Selenium	Se	79.2
Europium	Eu	152.0	Silicon	Si	28.3
Fluorine	F	19.0	Silver	Ag	107.88
Gadolinium	Gd	157.3	Sodium	Na	23.00
Gallium	Ga	69.9	Strontium	Sr	87.63
Germanium	Ge	72.5	Sulphur	S	32.07
Glucinum	Gl	9.1	Tantalum	Ta	181.5
Gold	Au	197.2	Tellurium	Te	127.5
Helium	He	3.99	Terbium	Tb	159.2
Holmium	Ho	163.5	Thallium	Tl	204.0
Hydrogen	H	1.008	Thorium	Th	232.4
Indium	In	114.8	Thulium	Tm	168.5
Iodine	I	126.92	Tin	Sn	119.0
Iridium	Ir	193.1	Titanium	Ti	48.1
Iron	Fe	55.84	Tungsten	W	184.0
Krypton	Kr	82.92	Uranium	U	238.5
Lanthanum	La	139.0	Vanadium	V	51.0
Lead	Pb	207.10	Xenon	Xe	130.2
Lithium	Li	6.94	Ytterbium	Yb	172.0
Lutecium	Lu	174.0	Yttrium	Yt	89.0
Magnesium	Mg	24.32	Zinc	Zn	65.37
Manganese	Mn	54.93	Zirconium	Zr	90.6
Mercury	Hg	200.6			

anode, and the electrode connected to the negative terminal of the battery is called the cathode.

We can see that the anode will be charged with positive electricity by being connected to the positive terminal of the

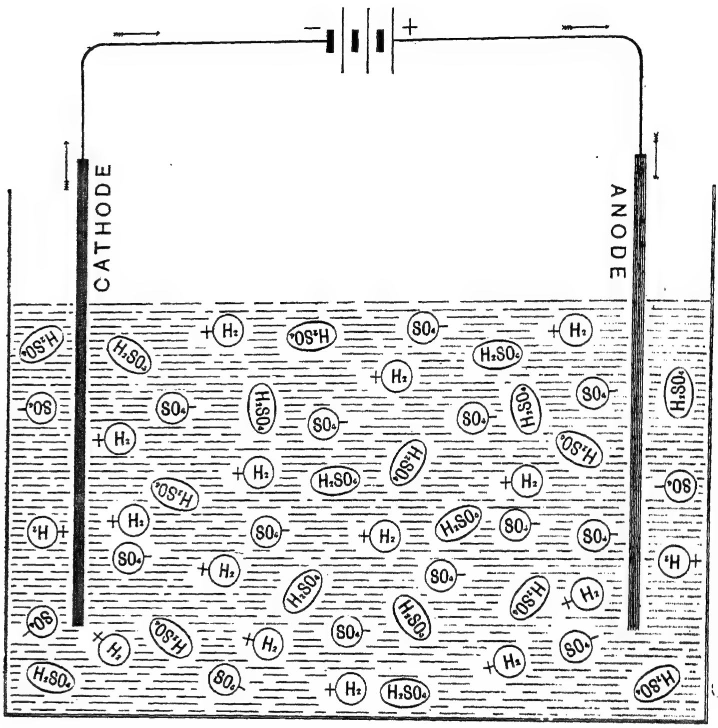


Fig. 107. Diagrammatic representation of passage of current (from external source) through sulphuric acid solution. (The arrows indicate the direction of the positive current.)

battery and the cathode will be charged with negative electricity from the negative terminal of the battery. The positive electricity on the anode will attract the negatively electrified ions (SO_4) in the sulphuric acid solution and the negative electricity on the cathode will attract the positively electrified ions (H_2) in the solution. There will therefore be a migration of H_2 ions to the cathode and SO_4 ions to the anode. It will soon be observed that

gas is bubbling off from each of the platinum plates and if some of the gas from the cathode is collected and tested, it will be found to be hydrogen.

At the anode the action which takes place is not so simple and the gas given off there is not SO_4 (which by the way is not capable of having a separate existence outside the solution). As the SO_4 collects on the platinum anode, it attacks the water in the solution. Water has the composition indicated by the formula H_2O, and SO_4 has a greater chemical affinity for hydrogen than oxygen has, so that what happens at the anode is this: each SO_4 takes up an H_2 from a molecule of water, forming a molecule of H_2SO_4 and liberating an atom of oxygen. The gas given off at the anode is therefore oxygen as may be verified by collecting and testing a sample. (There are also other less important secondary actions.)

The experiment here described is often referred to as the decomposition of *water* by electrolysis, electrolysis being the name given to the operation of passing a current of electricity through an electrolyte.

As a consequence of the action described we have various other effects. The negative electricity from the SO_4 ions which collect on the anode neutralises some of the positive electricity which it obtained from the battery and therefore there is a disappearance of positive electricity from the positive terminal of the battery. The positive electricity brought to the cathode by the H_2 ions causes positive electricity to pass into the negative terminal of the battery. The effect is therefore indistinguishable from the passage of a positive current from the positive to the negative terminals of the battery. (There is similarly a passage of negative electricity from the negative to the positive battery terminal; this is only another aspect of the same battery current. See page 7.)

When the migration of the ions begins to deplete the solution of ions (or ionised molecules) some of the combined or H_2SO_4 molecules in the solution split up into ions of H_2 and SO_4 and replenish to a greater or less extent the supply of "free" ions. As the action of the SO_4 ions at the anode restores the H_2SO_4 molecules, the process of the electrolysis may go on indefinitely

as far as the sulphuric acid solution is concerned; however, in time it may be observed that the solution in the neighbourhood of the anode contains a greater percentage of H_2SO_4 if precautions are taken to prevent the mixing up of the solution by the bubbling of the gases and convection of the liquid.

In all other cases the actions accompanying the passage of electricity through a solution are of a similar nature. These actions may be summarised as follows:

(1) Migration of positive ions to the cathode;

(2) Migration of negative ions to the anode;

(3) Secondary chemical actions take place at the electrodes according to the nature of the ions, the electrodes, and the solution *.

It is (3), the secondary chemical actions at the electrodes, that determine the chemical products obtained by the electrolysis. They are often very complicated and it is due to their obscuring the primary actions (1) and (2) that it was so long before these were understood. If the anode in the case given above had been zinc instead of platinum we should have had a quantity of zinc sulphate ($ZnSO_4$) formed and little or no oxygen given off. If a solution of copper sulphate ($CuSO_4$) had been employed instead of sulphuric acid, we should have had a deposit of copper on the cathode (and no hydrogen).

We are now in a position to explain the nature of the troubles encountered in the measurement of the resistance of an electrolyte (see page 122). When current is passed through a solution, in general, the electrodes become covered with a film of something different from the material of which they are made and therefore the resistance in the circuit is altered. This is especially the case when gas is formed at one or both of the electrodes, as a very thin film of gas may offer enormous resistance to the passage of electricity, all gases being insulators. In any case, the natures of the surfaces of the electrodes are changed more or less by the products of decomposition and we then have the equivalent of two different electrodes placed in the solution; this is, in effect, a voltaic cell

* As may be inferred, the secondary chemical actions depend also upon the chemical action which has already taken place and therefore upon the amount of the current, the diffusion in the electrolyte and its temperature.

which produces an electromotive force of its own,—a back E.M.F., as may be inferred from the principle stated on page 87. The term "polarisation" is used to denote these phenomena. It is the somewhat fortuitous and certainly unreliable character of these changes which is the source of trouble in the measurement of resistances of electrolytes.

To assist the student in determining in any particular case the arrangement of the ions, we may point out that the positive ion is either hydrogen, a metal, or some group of atoms which takes the place of hydrogen or metals in a similarly constituted substance. For example, in a solution of ammonium chloride (NH_4Cl) we can fix up NH_4 as the positive ion and Cl as the negative ion by following the corresponding constituents in such a series as:

Substance	Formula	Positive ion	Negative ion
Sulphuric acid	H_2SO_4	H_2	SO_4
Copper sulphate	$CuSO_4$	Cu	SO_4
Sodium sulphate	Na_2SO_4	Na_2	SO_4
Ammonium sulphate	$(NH_4)_2SO_4$	$(NH_4)_2$	SO_4
Hydrochloric acid	HCl	H	Cl
Sodium chloride	NaCl	Na	Cl
Ammonium chloride	NH_4Cl	NH_4	Cl

(See page 171 for the names of the elements represented by the various symbols.)

Electrolytic Refinement of Metals.

An important modern practical application of the principles enunciated in the foregoing is the purification of metals and even their extraction from their ores by electrolytic processes. In some cases the minerals from which the metal is obtained are brought into the form of a solution from which the metal is extracted by passing a current of electricity through it, the metal being deposited on the cathode. When the solution contains a variety of ingredients they may be separated out as far as is desirable by the method of crystallisation or other suitable means.

The electrolytic process has the advantage over the older purely chemical processes that it can be arranged to yield the predominant metal in a much purer state and traces of other metals present are not lost but may be recovered from the residual liquor when a sufficient amount of it has been collected to make

such an operation practicable. In this way the electrolytic process produces several metals as by-products.

The growth of the Electrical Engineering industries has produced a large demand for copper of great purity and the refinement of copper is now always done by the electrolytic method. The crude copper is made to serve as the anode in a copper sulphate solution and the action of the SO_4 ions on it when current is passed through the solution is to form fresh copper sulphate ($CuSO_4$), pure copper being deposited on the cathode. As the voltage required for each vat is only about 1 volt, a number of vats are connected in series and arrangements are also made for maintaining the solution in circulation so as to prevent the copper sulphate in it being concentrated in the neighbourhood of the anodes.

Copper is found in some parts of the world in the metallic state (it is called native copper) and it only requires purification. Some compounds of copper can be used as anodes for the electrolytic process as they stand, the SO_4 ions being able to decompose them and combine with the copper; other copper ores require the extraction of the copper as a preliminary to its refinement.

Quite a large number of metals are now produced by electrolytic processes but the procedure adopted in each case depends upon the properties of the particular substances and considerations of cost. In some cases the mineral conducts sufficiently well for its solution to be dispensed with; some minerals require subjection to a high temperature either to make them conduct or to facilitate the decomposition. The various methods of treatment that may be adopted are as follows:

(1) The metal is extracted from the mineral by chemical treatment and the crude metal so obtained is refined by electrolytic process.

(2) The mineral is used as anode in the electrolytic process.

(3) The mineral is used directly as electrolyte.

(4) The mineral is treated by the electric arc which subjects it to the combined action of electrolysis and high temperature.

The passage of a current of electricity through an impure solution does not always produce a pure metal; the separation

of metals by electrolysis depends upon the fact that under suitable conditions the electrolysis of a mixed solution produces first of all the metal which requires the smallest expenditure of energy to separate it, but the yield will not be pure if too large a current is employed or if the proportion of other substances present is too great. The current used and the proportion of impurities allowable depend on the nature of these impurities. It is quite common to use from 10 to 30 amperes per square foot of surface of cathode in refining copper, silver, lead or nickel, but much larger currents are occasionally practicable when the nature of the impurities allow it. Even then, however, there is a stage beyond which it is not safe to carry the electrolysis and the residual liquor requires treatment by crystallisation or otherwise to separate some of the substances contained in it before subjecting it to further electrolysis.

In the case of metals which are readily oxidised, it is usual to employ a mercury cathode (or cathode of some metal which alloys easily with the one to be separated) so that the formation of an amalgam (or alloy) protects the separated metal during the process. The pure metal is easily obtained from its amalgam by distilling off the mercury.

A number of electrochemical processes are now being worked, such as the production of calcium amide, carbide, carborundum, etc., and these are largely carried on in the neighbourhood of great water-falls where electric power from water-turbine driven dynamos can be readily obtained in vast quantities at an extremely low cost.

Electroplating.

Electroplating processes work on the same principles as some of the operations already described. Suppose that, for example, it is desired to nickelplate some piece of metal, *i.e.* cover it with a coat of nickel; all that is required is to prepare a solution of some soluble compound of nickel (nickel sulphate is suitable and easily procurable) and pass a current of electricity through it, using a piece of metal nickel as anode and the article to be nickel-plated as cathode. It is important to have the anode of some metal which will not contaminate the solution through the action

of the negative ions, and having a nickel anode not only satisfies this requirement but also replenishes the supply of the nickel compound in the solution (in the same manner as has already been explained on page 176 in the case of copper).

Plating with silver, gold or other metals is conducted on similar lines. The anode is made of the metal to be deposited (not always in the case of gold or very precious metals unless extensive operations are contemplated) and one of its compounds is dissolved to form the electrolyte. It is usual to put the anode at the bottom of the vessel containing the solution and suspend the cathodes (articles to be plated) in the solution by metallic hooks from a conductor above the solution connected to the negative terminal of the outside battery or dynamo.

There are several precautions necessary to obtain a deposit which will adhere firmly; the most important are that the articles to be plated should be *chemically clean* (free from every trace of oxide, grease, etc.) and that the current used should be properly proportioned to the surfaces of the articles plated. The cleaning process generally involves mechanical cleaning by rubbing, washing in caustic soda or potash to remove last traces of grease, dipping in dilute acid to remove oxide and rinsing in clean water.

As regards the current to be used, it is necessary to arrange its amount according to the surface of the articles to be plated. The amount of current per unit of surface is called the current density. The state of the deposit depends on the current density in the following manner:

Small current density gives a crystalline metal deposit,

Moderate current density gives a firm tough deposit (called "reguline" metal),

Great current density gives a soft black powder.

Of course, the proper current density to use depends not only on the metal to be deposited but also on the particular compound used to form the solution. The following table gives suitable current densities for some of the most common plating operations. As it is not necessary to arrange the current density with mathematical precision, the figures in the table are only given in round numbers, and when plating bodies of very irregular shape it is sufficient to make an approximation to the extent of their surface.

Current Densities for Electroplating.

	Amperes per square inch	Amperes per square foot	Volts
Copper, sulphate solution	.75 to 1.1	11 to 16	.7
Copper, cyanide solution	.04	5.5	3
Silver, cyanide solution ..	.03	4.5	1
Gold, cyanide solution ..	.007	1	4
Brass	.06	9	3.5
Nickel	.02 to .04	3 to 5.5	2 to 3

It will be noted that greater current densities are frequently used in the electrolytic refinement of metals than are permissible for electroplating. This is due to the fact that in electroplating the firmness of the deposited metal is of the first importance (its purity is arranged for in compounding the electrolyte and in the case of brassing and bronzing, the electrolyte is deliberately made up of a mixture so as to deposit an alloy instead of a pure metal), whereas in the refinement of metals the important thing is the purity of the deposit and, as a rule, its firmness is not of much consequence as the metal has to be worked up afterwards into bars, sheets, wires, etc.

Electroplating is not always a matter of difficulty but when carried out on a commercial scale, economic and other considerations require attention to be given to a number of details which we cannot enter into here and for which special books on the subject should be consulted.

Among the metals which have been deposited electrolytically are: aluminium, antimony, bismuth, cadmium, chromium, cobalt, copper, gold, magnesium, manganese, nickel, palladium, platinum, silver, tin. Besides ordinary electroplating the process is also applied to the production of electrotypes, medallions, statues. When—as in the last mentioned cases—the metal deposit is required to take the form of some object but not to be an adhering film upon it, a mould is made from the object and the deposit is made to form on the mould from which it is detached when the deposit is sufficiently thick. The mould may be made of any convenient substance, *e.g.* plaster of paris, and it can be made to act as a cathode by covering its surface with a thin film

of a conducting substance such as a thin coat of carbon dust or plumbago.

The most convenient way for amateurs to electroplate is by the use of galvanit. The nature of the action in this case is similar to that already described but the currents of electricity are produced in the same sort of manner as the local action in a voltaic cell. See page 185.

// *Laws of Electrolysis.*

The relationships between the electrical and chemical actions taking place when a current of electricity is passed through an electrolyte were discovered by Faraday and they may be stated briefly as follows:

(1) The amount of chemical decomposition is proportional to the quantity of electricity passed through the electrolyte.

(2) The products of decomposition produced by equal quantities of electricity are chemically equivalent.

These laws admit of a simple explanation in terms of ions. Referring once more to the fundamental principles stated on pages 170 and 174,—viz., that in an electrolyte a certain proportion of the molecules of the dissolved substance exist in the ionised state, split up into equal numbers of positively electrified ions and negatively electrified ions and that the passage of a current of electricity through the electrolyte is accomplished by the migration of positive ions to the cathode and negative ions to the anode through the influence of the electricity generated by the external dynamo or battery,—we need only add that when the positive ion is hydrogen each atom of that hydrogen has a definite fixed amount of positive electricity, the same amount for each atom of hydrogen no matter what the composition of the electrolyte may be. This definite fixed amount of electricity carried by each atom of hydrogen in hydrogen ions is called an electron and it is calculated to be approximately $\frac{22}{10^{20}}$ coulomb. The negative ion in each case carries as much negative electricity as the positive ion carries of positive electricity; so that each negative ion has the same number of negative electrons as the positive ion has of positive electrons.

When the positive ion is not hydrogen, each positive ion carries the same amount of positive electricity as the quantity of hydrogen which takes its place in the correspondingly constituted substance containing hydrogen only in its positive ion. Thus in the case of sulphuric acid (H_2SO_4) each positive ion (H_2) carries two positive electrons and each negative ion (SO_4) carries two negative electrons. In solutions of copper sulphate ($CuSO_4$) each positive ion (Cu) carries two positive electrons, and each negative ion (SO_4) carries two negative electrons. Referring to the list of substances on page 175, we see that there would be one positive electron for each Na atom and for each NH_4 group and one negative electron for each Cl atom in the ions there enumerated.

As the passage of the current through an electrolyte depends upon the electricity handed over to the electrodes by the ions, and as each ion in a solution of a given substance has the same number of electrons and all electrons represent the same amount of electricity, it is obvious that the quantity of electricity passed through the electrolyte is proportional to the number of ions which come into contact with the electrodes, that is, to the amount of the dissolved substance which is decomposed.

Likewise, in comparing one dissolved substance with another it is seen that the number of positive electrons to each positive ion is equal to the number of hydrogen atoms in the correspondingly constituted substance containing hydrogen atoms alone as its positive element, that is to say, each positive ion has the same number of electrons as its chemical equivalent (expressed in hydrogen atoms). Therefore each coulomb of electricity passed through electrolytes is accompanied by amounts of decomposition which are chemically equivalent.

It should be explained that some elements are only capable of supplanting (or combining with) hydrogen at the rate of atom for atom; these are called monovalent elements. Other elements are capable of making one of their atoms supplant two hydrogen atoms; these are divalent. Others again are trivalent, and so on. The valency of an element is measured by the number of hydrogen atoms each one of its atoms can supplant; some elements have different valencies in different compounds. The chemical

equivalent of an element in any given condition is measured by the quotient of its atomic weight divided by the valency.

The reader will now be in a position to understand how it is possible to specify currents of electricity by the amount of chemical decomposition produced in a given time. This same specification can also be applied to calculate the amount of electricity required to refine a given amount of metal*. The ampere is defined as the current which produces a deposit of .00111800 grammes of silver in one second (from silver nitrate, $AgNO_3$; corresponding hydrogen compound HNO_3). From this we can calculate the following:

Element	Symbol	Atomic Weight	Valency	Chemical equivalent	Grammes deposit per ampere per second
Silver	**Ag**	**107.88**	**1**	**107.88**	**.00111800**
Copper	Cu	63.57	2	31.785	.0003294
Nickel	Ni	58.68	2	29.34	.0003040
Cobalt	Co	58.97	2	29.485	.0003056
Gold	Au	197.2	3	65.73	.0006812
Platinum	Pt	195.2	~~2~~ 4	48.8	.0005057
Hydrogen	H	1.008	1	1.008	.000010446

The Voltaic Cell.

A voltaic cell is a device for obtaining currents of electricity by means of chemical action, and consists essentially of two electrodes of different materials placed in some electrolyte. It originated in the discovery of Volta that when two metals are placed in contact a difference of potential is produced between them, or in other words, one of them becomes positively electrified and the other one becomes negatively electrified. This phenomenon seems to accompany the placing in contact of any two different substances, and it accounts for the production of electricity by friction, the friction simply serving to bring a greater number of points into contact. In the case of good conductors the electrifica-

* The amount of metal deposited in electroplating with a given current in a given time will often be somewhat less than the amount calculated from the table given above owing to the action of ingredients put in the electrolyte to improve the physical character of the deposit.

In measuring currents by electrolytic methods it is important to avoid conditions affecting the *amount* of the deposit per ampere per second.

tion takes place without the necessity of establishing contact at a large number of points.

In the earliest forms of voltaic cell, zinc and copper were used for the electrodes and sulphuric acid for the electrolyte. The nature of the action of such a cell will not be difficult to

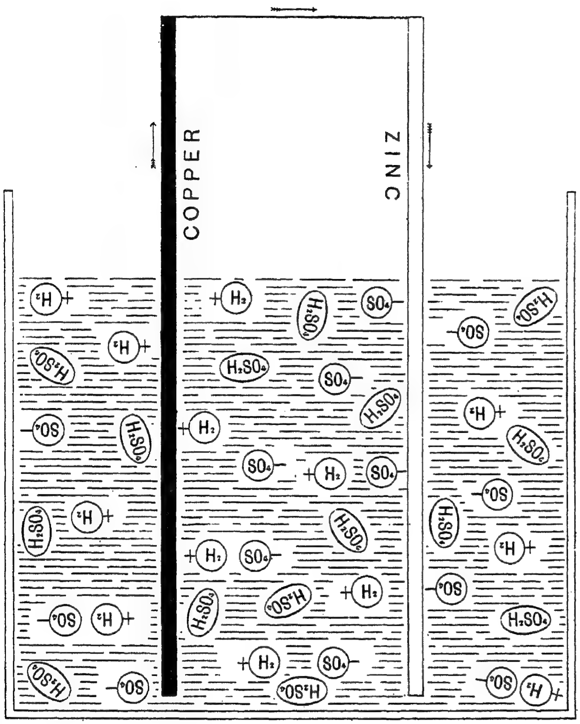


Fig. 108. Diagrammatic representation of production of current in a primary cell. (The arrows indicate the direction of the positive current.)

follow with the help of Fig. 108. When contact is established between the zinc and copper by closing the external circuit, the zinc becomes positively electrified and the copper negatively electrified; the result is that the negative ions (SO_4) in the sulphuric acid are attracted to the zinc and the positive (H_2) ions are attracted to the copper; the migration of the ions and the handing over of their electricity to the electrodes causes a

current of positive electricity to flow through the external circuit from the copper to the zinc. (Negative electricity travels the opposite way round the circuit, but as already explained on pages 7 and 173, that is but another aspect of the same current; the direction of the current is always taken as that of the positive electricity). As the current in the external circuit goes from copper to zinc, the copper electrode is called the positive terminal of the cell, although it is negatively electrified by the contact effect*.

As will be inferred from the general statement on page 174, polarisation and its accompanying back E.M.F. is set up by the passage of the current in a voltaic cell. In the cell described, the SO_4 ions coming in contact with the zinc form zinc sulphate ($ZnSO_4$) which dissolves in the electrolyte and causes no trouble (for some time). The H_2 ions which reach the copper electrode cover it with a film of hydrogen gas which produces a back E.M.F. in addition to increasing the (internal) resistance of the cell.

The modifications made on this primitive form of cell have all had for their object the getting rid of the hydrogen which collected on the copper electrode. An oxidising agent was generally employed for this purpose, in which case platinum—and subsequently carbon, which is cheaper than platinum—was substituted for copper. In the bichromate cell, potassium or sodium bichromate was employed as the oxidising agent. Chromic acid is better, as it does not give rise to the formation of crystals of the chrome-alum variety. Nitric acid was adopted by many, as in the one time well-known cell of Bunsen, to effect the oxidation of the hydrogen. In such cells, the electrolyte was in two parts separated by a porous partition which left the two parts in contact but more or less obstructed their diffusion. On one side of the porous partition there was the sulphuric acid with the zinc electrode in it; on the other side there was the nitric acid with the carbon electrode in it. Such cells (with nitric acid) could not be left fitted up for long periods.

* Besides the contact difference of potential between the zinc and the copper, there is a contact difference of potential between the zinc and the sulphuric acid, and a contact difference of potential between the copper and the sulphuric acid, but the first mentioned of these predominates. The nature of the metal in the external circuit is a matter of indifference; Volta found that in a series of metals in contact the extreme difference of potential depended only on the extreme metals.

The Daniell cell retained the copper electrode but had a porous partition with copper sulphate solution in place of nitric acid. The H_2 ions attacked the copper sulphate forming H_2SO_4 (sulphuric acid) and liberating Cu ions which formed a deposit of copper on the copper electrode, thus leaving its nature substantially unaltered.

Local Action.

Another source of trouble in voltaic cells is what is called "local action." If there is any impurity or a speck of foreign matter on the surface of the zinc, its contact with the zinc produces a difference of potential which sets up a current of electricity flowing into the zinc through the point of contact and returning through the electrolyte. This current does not reach the external circuit, and might be ignored but for the fact that it also is accompanied by the formation of zinc sulphate (or the compound of zinc corresponding to the electrolyte employed) at the expense of the zinc, so that while such currents cannot be made to serve any useful purpose in the work for which the cell is employed, they help to consume the zinc. The method employed to reduce local action to a minimum is to "amalgamate the zinc," that is, to cover it with a film of mercury which short-circuits the local action without preventing the SO_4 or corresponding ions from getting at the zinc owing to the formation of an amalgam of zinc and mercury.

The production of electricity from cells such as have been described is much too costly to permit of their employment on a commercial scale; indeed, the cost of the zinc alone is prohibitive. Cells with a zinc electrode are now obsolete with the solitary exception of the Leclanché cell and its modifications which are still employed for working electric bells and sundry purposes not requiring much output of current. For other purposes requiring the employment of cells, storage cells are now used.

Leclanché Cell.

The Leclanché cell has zinc and carbon electrodes, and the electrolyte is a solution of ammonium chloride (NH_4Cl); the oxidising agent is manganese dioxide (MnO_2). In the ordinary

form of Leclanché the manganese dioxide is mixed with carbon dust and compressed into slabs of which one is tied up to each side of the carbon plate. In the "carporous" form of Leclanché the carbon electrode is made in the form of a round perforated cylinder inside which there is a long narrow porous pot; the space between the porous pot and the hollow carbon cylinder is filled with a mixture of manganese dioxide and carbon grains, and the zinc rod is placed inside the porous pot. Still another arrangement of the Leclanché cell is illustrated in Fig. 109.

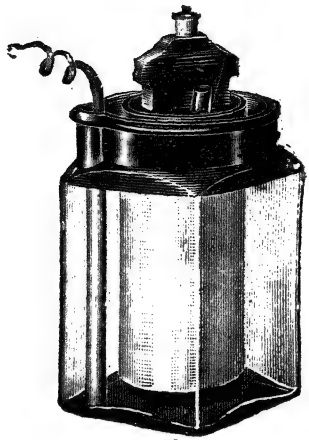


Fig. 109. Leclanché Cell.

During the passage of the current the Cl ions travel to the zinc, and on reaching it combine with zinc to form zinc chloride; the NH_4 ions travel towards the carbon, and on reaching any part of it split up into NH_3 (ammonia) and H (hydrogen). The ammonia dissolves in the electrolyte; the hydrogen only disappears at the rate at which the manganese dioxide is capable of oxidising it, and the cell is thus incapable of maintaining its full initial current for more than a short time, owing to the increase of (internal) resistance and back E.M.F. The chief merit of the cell is the small amount of deterioration of the zinc which takes place while the cell is standing idle. Also, the cell may still be serviceable for intermittent work after the manganese dioxide is exhausted, owing to the solution and evaporation of the hydrogen during the periods of idleness (when current is not being taken from it).

Dry Cells.

Dry cells are simply Leclanché cells made up in a form so that there is nothing spillable. The zinc electrode is made of sheet zinc into the form of a pot, and serves also as the vessel containing the rest of the cell, thus dispensing with glass boxes. A paper or cardboard outer case is put over the zinc to insulate and protect it.

The electrolyte or ammonium chloride solution is made into a paste by the use of sawdust, flour or plaster of paris, or some mixture containing these ingredients, and to prevent it hardening glycerine and a deliquescent substance (*e.g.* calcium chloride) is also included. The carbon electrode and its adjacent mixture of manganese dioxide and carbon grains is placed down the centre of the cell —but not far enough to touch the zinc—and is sometimes provided with a muslin bag to keep everything in place while the

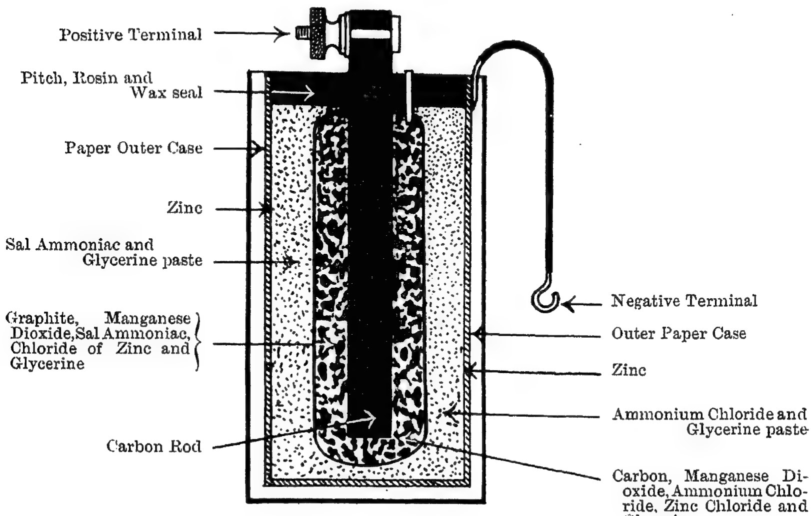


Fig. 110. Dry Cell.

cell is being filled. When the cell is made, the carbon electrode is held in position by sealing in the top with marine glue (or pitch). A vent hole is provided for gases or air to escape (or enter) as required to accommodate the changes of temperature, etc., of the cell, and sometimes also the cell is made long enough to permit of a loose packing of sawdust between the electrolyte and the marine glue seal. Fig. 110 shows (in section) an arrangement which may be taken as fairly typical of dry cells *.

* Bottone's Primary Batteries contains details of practically every make of cell.

Batteries.

When it is desired to employ a greater electromotive force than that obtainable from one cell, it is necessary to use the requisite number of cells connected in series ; such an arrangement is called a battery.

The larger the individual cell is made, the greater the current that may be obtained from it under given conditions. The internal resistance of a given type of cell is roughly inversely proportional to its linear dimensions. Cells may be employed connected in parallel as an alternative to employing larger cells, and batteries of cells may be employed connected in parallel. In such cases it is necessary to have the same number of cells in each branch of the circuit to prevent the waste that would otherwise take place through the several batteries sending currents through each other. The E.M.F. of such combinations is that of each cell multiplied by the number of cells in series, and the internal resistance of the combination is that of each cell multiplied by the number of cells in series (in one battery) divided by the number of batteries in parallel (assuming the individual cells are identical in E.M.F. and resistance).

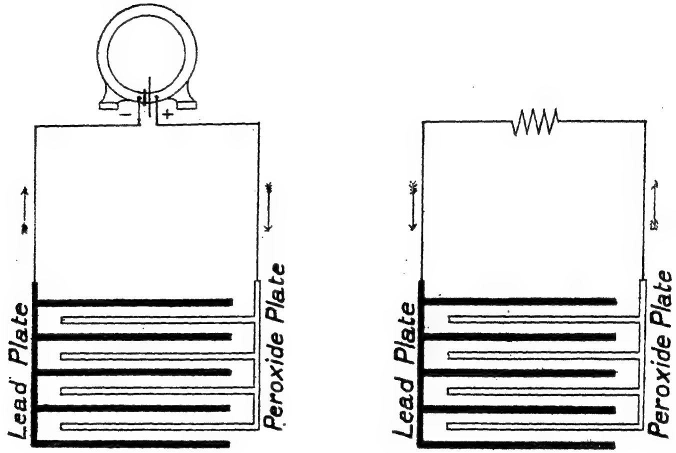
The combination of cells which produces the greatest current in a given external circuit from a given number of cells is that in which the internal resistance of the cells as arranged is equal to the resistance of the external circuit.

These remarks also apply to storage cells, but it is seldom worth while to arrange storage cells in parallel. Compared with so-called primary cells of anything like the same size, storage cells have much smaller internal resistance and much steadier E.M.F. The E.M.F. of primary cells varies with the type and state of the cell, but it is generally between 1 and 2 volts. The E.M.F. of any make of storage cell of the ordinary lead type is always near 2 volts (if the cell is in working order), and the E.M.F. of an Edison storage cell is near 1.2 volts in normal conditions.

Storage Cells.

The appliances which are described by the names "storage cells," "secondary cells," "accumulators," only differ from the cells previously described in the manner in which the consumed material

out alone, the H_2 and the SO_4 ions travel in the opposite directions respectively to that mentioned above and the H_2 ions reaching the lead electrode form H_2SO_4 by their action on the $Pb_m (SO_4)_n$; the SO_4 ions reaching the peroxide electrode attack the water of the electrolyte, combine with the hydrogen of the water (H_2O) to form sulphuric acid (H_2SO_4), thus liberating oxygen which combines with the $Pb_mO_{m-n} (SO_4)_n$ increasing the amount of oxygen and liberating more SO_4, which does the same thing once more *.



Charge

Discharge

Fig. 111.

When the operation of restoring the lead and lead peroxide is complete, and the current is still continued in the direction for charging, the electrolyte is decomposed in the manner indicated on page 173 and gas is given off from the electrodes. The bubbles of gas ascending through the liquid electrolyte give it a milky appearance, and "milking" is therefore one of the indications of a cell being fully charged.

Fig. 111 shows diagrammatically the directions of the charging and discharging currents in relation to the respective electrodes.

* It is not possible here to enter into a full discussion of all the theories that have been held respecting the chemical actions of storage cells. We content ourselves with giving briefly that which there is reason to believe is the most satisfactory so far.

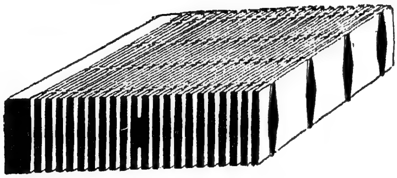
Only one cell is shown, but the arrangement also applies to a battery with the free terminals of the battery substituted for the respective cell terminals. In the actual cells the electrodes are in the form of flat plates alternately positive (peroxide) and negative (lead), alternate plates being connected to each cell terminal as shown in the Fig. Generally there is one more negative plate than positives. The positive plate has a lead foundation to strengthen it, hold the peroxide, and to conduct the current to or from the peroxide. The negative plates have a colour more or less like lead, but the positive plates are dark brown or chocolate coloured. When the cell is fully charged, the positive plates are darker in colour than after discharge; in fact, to a trained eye, the colour of the plates is a good indication of the state of the cell.

Planté Process.

Storage cells are made by one of two processes called the Planté process (after the inventor) and the paste process (invented by Camille A. Faure in 1881).

Plates made by the Planté process are often called "formed" plates, from the nature of the process which starts with lead in the first instance for both positives and negatives. Formed plates are now nearly always built up of corrugated strips of lead which have a framework of lead cast on to them so that the edges of the strips are exposed on the flat face of the plate. See Fig. 112. The forming process consists of placing the plates in sulphuric acid—much in the same way as when the cell is in use—and passing current through them as in the process of charging. The chemical action is similar to that already described for the charging process, and the positive plate becomes covered by a film of peroxide. As originally carried out by Planté, this process was succeeded by a period of rest in which the oxidation of the lead penetrated further owing to a sort of local action between the lead and peroxide (at the expense of the oxygen of the peroxide); then it was discharged in order to come back to the condition of lead, but with a spongy structure on the surface. Then the whole round of charging, etc., was repeated until the final charge. The object of these manoeuvres was to have the plates covered with

a sufficient thickness of active material in a state capable of reacting readily to the chemical changes required. The same result is now obtained by forming the plates in an electrolyte containing not only sulphuric acid but some nitrogen salt (sodium nitrite preferably). When formed, the plates are transferred from this forming electrolyte.



Full-size section of Planté Positive Plate.

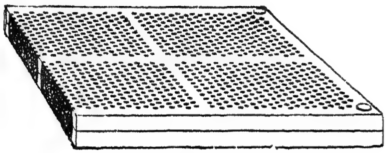
Fig. 112. Planté Positive Plate (D. P. Battery Company).

Paste Process.

Plates made by the paste process start with a grid of lead the interstices of which are filled with a paste made of minium (red lead) mixed with sulphuric acid for positive plates and litharge (PbO) and sulphuric acid for negative plates. Much ingenuity has been exercised in producing grids from which the pellets of paste are not liable to drop out when the cell is in use. Some

makers now make the grid of their paste plates in two halves with fairly large apertures and a fine perforated web of lead on the sides that are going to be on the outside of the plate when finished. The paste is filled in before the two halves of the plate are put together. See Fig. 113.

Paste plates are brought to their proper condition by the process of charging in sulphuric acid solution alone. The first



Section of Sponge Negative Plate.

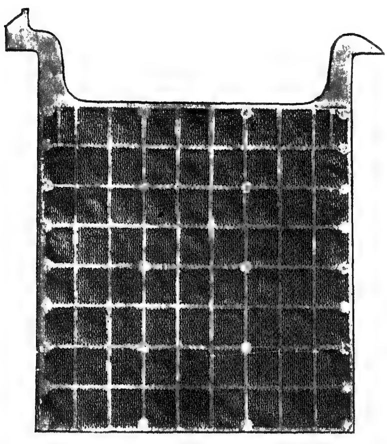


Fig. 113. Sponge Negative Plate (D. P. Battery Company).

charge is, of course, much longer than is required for subsequent charges after the plates are brought to the normal working state.

It is now quite common to make storage cells with Planté positives and paste negatives. Experience has shown, as might have been expected, that positive plates have not as long a "life" as negative plates in the same cell, and Planté positives can be made to stand a greater number of amperes per square foot of plate surface than paste positives.

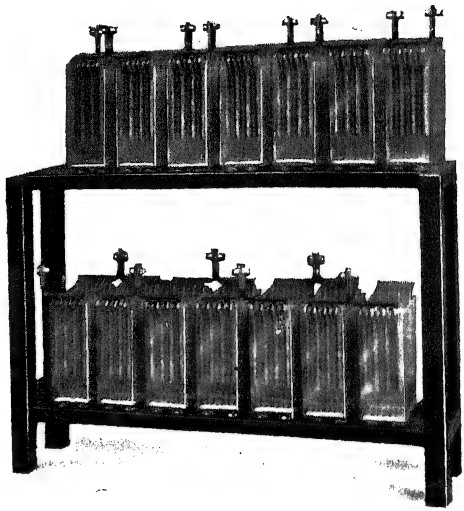


Fig. 114.

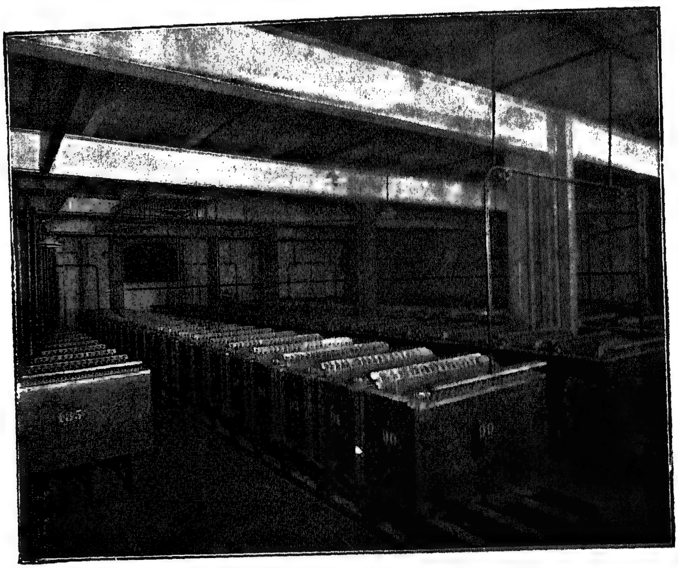


Fig. 115. E.P.S. Storage Battery

Storage Battery Installations.

Storage cells installed in permanent positions are generally mounted in glass boxes or lead-lined teak boxes placed on suitable tables. See Figs. 114 and 115. The boxes are insulated from the tables by glass insulators containing oil (see Fig. 116) and to prevent these glass insulators from getting cracked by the weight of the cell, a tray containing sawdust or some other kind of packing is placed between the bottom of the glass box and the glass insulators. The positive and negative plates inside the cell are separated by glass rods or sheets of some porous insulating material. At one time it was usual to support the plates on the bottom of the glass box, but it is now usual to suspend them from lugs resting on the edge of the box or glass slabs standing on edge. Ample space is allowed between the floor of the box and the lower edges of the plates so as to keep them clear of any deposit that may collect in the bottom of the cell. Exposed terminals are generally protected from corrosion by acid fumes by being covered with anti-sulphuric enamel, and connecting bolts should either be so treated or smeared with vaseline. In batteries permanently installed it is common to make the connections between cells by "burning" together the lead terminal pieces to adjacent cells. See Fig. 115.

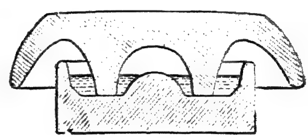


Fig. 116. Sectional View of Glass Insulator.

Lead-lined teak boxes are generally used for storage cells which require to be moved about. See Fig. 117. For small portable storage cells celluloid boxes are frequently employed.

The room in which a storage battery is installed should be well ventilated and should be partitioned off from that containing the generating plant. In private installations it is best to employ a simple shunt-wound continuous-current generator for charging storage batteries, in which case a shunt regulator (*i.e.*, an adjustable resistance in the field circuit of the dynamo) is necessary for the adjustment of the voltage. When a compound-wound generator is used, there is a liability of the battery running the generator as a motor when connected up for charging, and to prevent accidents

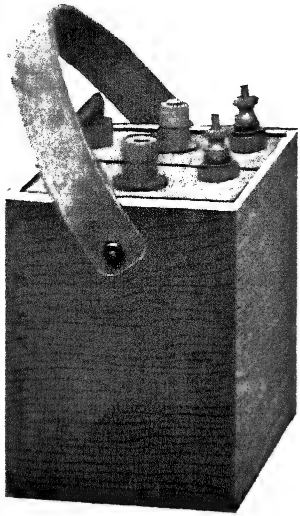


Fig. 117. E.P.S. Portable Accumulator.

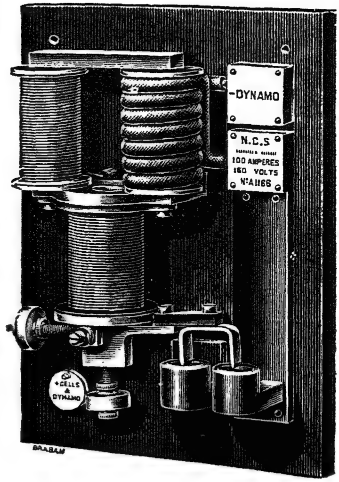


Fig. 118. Crawley Automatic Accumulator Switch (Nalder Bros. & Thompson).

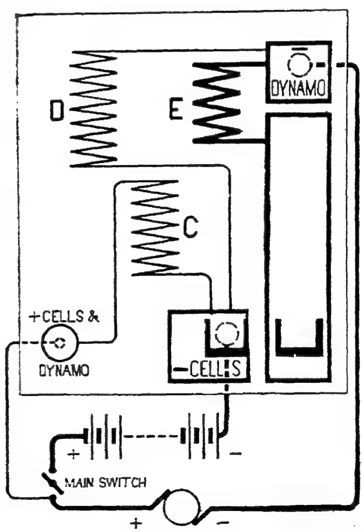


Fig. 119. Diagram of connections of Crawley automatic accumulator switch.

of this kind an automatic cut-in-and-out switch should be used. Such a switch is a device for disconnecting the battery from the dynamo when the current passing between them does not go in the proper direction for charging. Fig. 118 illustrates the Crawley automatic accumulator switch, which is one of the best for this purpose, and Fig. 119 gives its diagram of connections. In Fig. 119, the conductors indicated by thick lines should be of sufficient cross-section to carry the full current of the installation.

Treatment of Storage Batteries.

In normal circumstances the installation and first charge of a storage battery will be carried out under the supervision of the makers, who also supply directions as to its care and treatment. It is important that the maker's instructions be faithfully carried out if the battery is to last well. The chief matters requiring attention are the following:

(1) the discharge of the battery should not be carried too far;

(2) the battery should not be left for long intervals in a discharged condition;

(3) care should be taken to avoid mistaking a partial charge for a complete charge.

With regard to (1), it is a safe general rule not to discharge a battery beyond the point at which the E.M.F. falls to an average of 1.8 volts per cell *. The trouble connected with carrying the

* As will be explained later (page 200), the E.M.F. to which a storage cell may be safely discharged depends upon the rate of discharge or the discharging current. When a fully charged cell is discharged at a current of about three times the amount of the normal charging current (one hour rate of discharge) the E.M.F. per cell may be carried as low as 1.7 volts; at a ten hour rate of discharge the limit is 1.83 volts per cell. For intermediate rates of discharge it is near enough to take the limiting voltage at the proportionate intermediate amount.

The limits specified above apply to the discharge of cells which are in the *fully* charged condition at the commencement of discharge, and merely increasing the discharging current does not warrant a reduction in the limiting voltage to the extent specified above in the case of cells which have been partly discharged at a lower rate.

A simple ingenious instrument (E.P.S. Overload Detector) enabling the working of a storage battery to be controlled in accordance with the required limitations of discharge, etc., has been devised by R. Rankin. For particulars of this

discharge too far is due to the formation on the plates of $PbSO_4$, the normal sulphate of lead, a white stable compound which cannot take part in the electrochemical action of the cell. The formation of this substance represents a corresponding loss of active material in the cell; it interferes with the passage of the ions; when started, it spreads with increasing rapidity. The presence of this white sulphate in a cell can be detected by its colour. Immediately there is any sign of it, the only thing to be done is to carry out a prolonged charge, and if this is performed in time, it may effect the removal of the white sulphate and prevent the spread of its formation.

The name "sulphating" is given to the formation of the normal stable white sulphate, and this is the one malignant battery disease the prevention of which should receive the unremitting attention of the storage battery attendant.

With regard to (2), it is always best to recharge a battery immediately after it has been used to give out current, but in any case not more than a few days should be allowed to lapse before it is again fully charged. It sometimes happens that the battery is not required for a long interval (for example, during holiday times), and in such cases the battery should be fully charged before leaving. Sulphating is frequently caused by leaving batteries for long intervals in a partly discharged condition.

With regard to (3), it occasionally happens in private installations that the battery attendant shows a disposition to charge the battery at a rather greater current than the normal amount specified, as he finds that in this way the cells begin to milk sooner, and he therefore concludes that the charging is being completed in less time. What is really happening is that he is supplying electricity faster than the electrochemical action can penetrate beyond the merest film on the surface of the plates, and the surplus which cannot be "soaked in" produces gaseous decomposition.

instrument and its uses, see Rankin's article on "A new instrument for the control of storage batteries" in the *Electrician*, Vol. 73, page 449 (June 19, 1914).

In private installations it will generally be wiser to adhere rigidly to the limit of 1.8 volts per cell unless an appliance like the one just mentioned is provided.

Milking is not the only indication of the state of charge of a cell. There are three other things which serve to indicate the state of a cell and which should receive attention :

(1) the electromotive force or voltage ;
(2) the specific gravity of the electrolyte ;
(3) the colour of the plates.

During the process of charging the E.M.F. of the battery rises, and when the charge is complete the charging E.M.F. should not be less than 2.4 volts per cell at the ordinary charging current. When charging has been stopped the E.M.F. of the battery should be about 2.1 volts per cell if it is fully charged. When current is taken out of the cells the E.M.F. falls fairly rapidly at first to practically 2 volts per cell ; thereafter the E.M.F. falls but slowly until the battery begins to reach the neighbourhood of its reasonable limit of discharge.

The specific gravity of the acid in a cell increases during charging and decreases during discharge. The usual limits between which the specific gravity varies is about 1.165 to 1.200, but makers supply particulars for their respective cells, and hydrometers can be obtained with the appropriate specific gravities prominently marked.

The positive plates of storage cells show the most marked contrast in colour between the charged and discharged conditions, being of a very dark shade when fully charged.

The electrolyte in a storage cell suffers gradual diminution owing to loss through evaporation and milking. As it is only water which is lost in these ways, the loss is to be made good by the addition of pure water only. Distilled water should be used for this purpose, as tap water is practically always unsuitable on account of the hardness and other "impurities" which may be beneficial for drinking purposes but are always deleterious to storage cells. The level of the electrolyte should be maintained as nearly as possible at a uniform height covering the plates, not only because it is important to keep the plates covered, but the specific gravity indications are slightly affected by fluctuations in the amount of water in the electrolyte.

Capacity of Storage Cells.

The amount of electricity which may be obtained from the discharge of a fully charged cell is called its capacity, and this is always specified in ampere-hours (the coulomb is an inconveniently small unit for this purpose). However, the ampere-hours obtained from a cell depend upon the rate of discharge, that is, the amount of the current at which it is discharged. At high rates of discharge, the active material in direct contact with the electrolyte is exhausted before the inner layers have had time to be

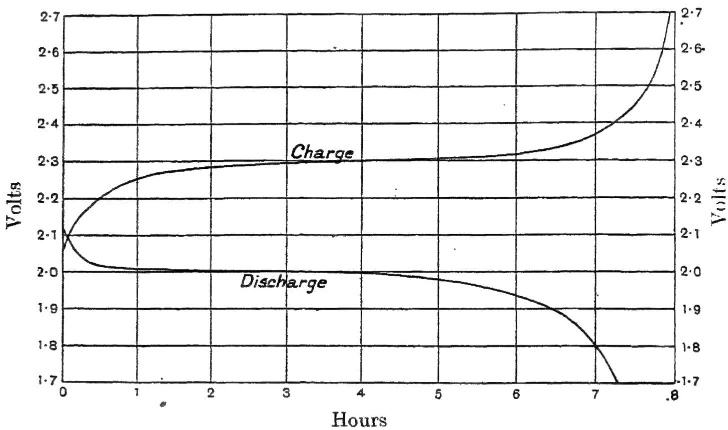


Fig. 120. Typical Charge and Discharge Curve of Lead Storage Cell.

greatly affected and the E.M.F. of the cell begins to fall rapidly—and if discharge is carried far enough the E.M.F. would disappear—before the whole of the active material had taken part in the action. It is therefore obvious that the full output of the cell cannot be obtained at high rates of discharge; in other words, the effective capacity of the cell depends upon the rate of discharge, and is smaller the greater the discharging current.

At high rates of discharge a cell may safely be discharged to a lower voltage than would be safe at a moderate or small rate of discharge owing to the recuperative effect of the active material which cannot be completely discharged; indeed, a cell which has been subjected to a rapid discharge recovers some of its E.M.F. on

standing. Nevertheless, the E.M.F. of a cell on discharge falls so rapidly below 1.8 volts that carrying the discharge beyond that point only makes a comparatively small addition to the output. Fig. 120 shows curves which may be taken as typical of the manner in which the E.M.F. varies during charge and discharge respectively.

At one time it was common to find cells which could not safely be discharged at greater currents than a four hour rate, and cells of such kinds may still be in actual use in some places. The damage done to such cells by large discharge currents consisted in dislodging the paste or active material or "buckling" the plates. Modern cells will stand a one hour rate of discharge. The following table gives in round numbers approximate average figures for the capacity of cells at various discharge rates. The capacity at a seven hour rate is put at 100, and the capacity at other rates therefore appears as a percentage of that amount. The normal charging current is generally about equal to the discharge current of the seven hour rate, but the charging current may be increased to $1\frac{1}{2}$ times that amount.

Rates of Discharge.	1 hour rate	2 hour rate	3 hour rate	4 hour rate	5 hour rate	6 hour rate	7 hour rate	8 hour rate	9 hour rate	10 hour rate
Output in ampere-hours	51	67	77	85	92	97	100	102	104	105
Discharging current in percentage of normal charging current ..	360	230	180	150	130	110	100	90	80	75

The energy efficiency of the storage cell, that is, the ratio of the energy obtained from the cell to the energy expended in charging it, depends upon the rate of charge and the rate of discharge, but it rarely exceeds 80 per cent. under the best conditions (about seven hour rate) and is reduced by the use of high rates of discharge at a rather greater rate than the ampere-hour output.

The Edison Battery.

So far we have been referring entirely to lead storage cells, that is, cells having electrodes of lead and lead peroxide. The Edison storage cell is very different in its construction, which is

so much superior in mechanical strength as to dispense with any special precautions in its use. The Edison cell dates from 1901 but the present-day form was introduced in 1908.

The Edison accumulator has electrodes of nickel oxide and iron, and the electrolyte is an alkaline solution (potassium hydrate).

Fig. 121. Positive or Nickel Tube of Edison Accumulator.

The positive plate is built up of perforated nickel-steel tubes (see Fig. 121), each of which is made from a thin strip of nickel-steel coiled into a spiral of $\frac{1}{4}$ inch diameter, the edges being lapped over to prevent re-opening, which is further secured by eight steel bands encircling the tube. The tube is filled with alternate

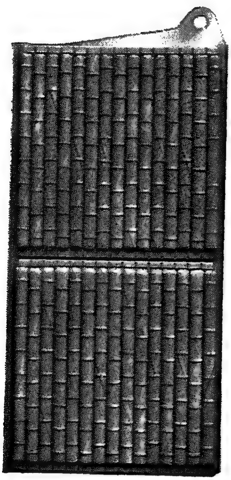


Fig. 122. Edison Positive Plate.

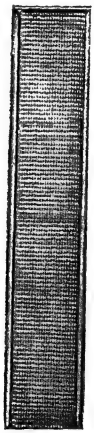


Fig. 123. Negative or Iron Pocket of Edison Accumulator.

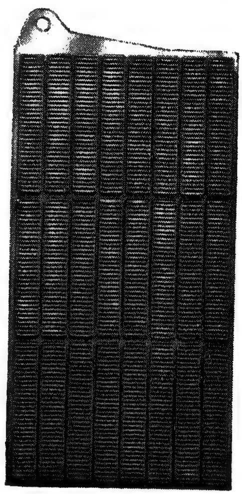


Fig. 124. Edison Negative Plate.

thin layers of nickel hydrate (green) and very fine flakes of metallic nickel rammed down tight. The function of the nickel flakes is simply to improve the conductance, nickel hydrate being rather a poor conductor. The complete positive plate consists of an

assemblage of loaded tubes in a stamped frame of nickel-steel, as shown in Fig. 122.

For the negative plate, finely divided iron oxide (incorporated with a small proportion of mercury to improve conductance—the mercury has no other effect) is loaded into rectangular pockets made of very thin finely perforated nickel-steel strip (see Fig. 123). The filled pockets are assembled in a steel frame (Fig. 124) and

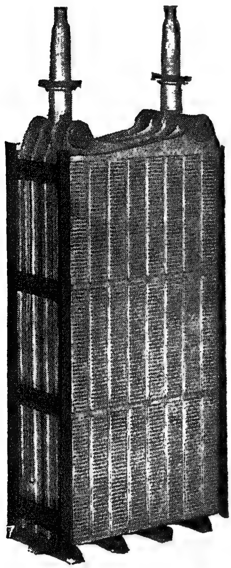


Fig. 125. Edison Cell assembled.

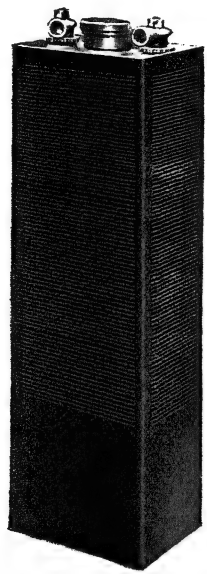


Fig. 126. Complete Edison Cell in Nickel Steel Container.

subjected to heavy die pressure which at one and the same time compresses the oxide, corrugates the faces of the pockets and swages over their edges into firm engagement with the steel frame.

The assembled plates (Fig. 125), alternately positive and negative, are insulated from each other by thin strips of ebonite and are mounted in a nickel-steel outer case, care being taken to insulate the plates from the case (see Fig. 126). The cover of the cell is fitted with a gravity valve cap which allows the escape of gas whilst preventing ingress of air which would act on the electrolyte and weaken the solution. The valve lifts with the cap cover to

enable filling up with the electrolyte to be done. Batteries of Edison cells are mounted in hardwood crates, as shown in Fig. 127.

Owing to the fact that the active material of the Edison cell cannot be dislodged, no damage can be done by excessive charging or discharging, nor does it appear to suffer from standing idle in the discharged condition. Fig. 128 shows a typical charge and discharge curve, and Fig. 129 shows the result of tests before and after standing six months in a completely discharged condition. This valuable property is particularly desirable for ignition

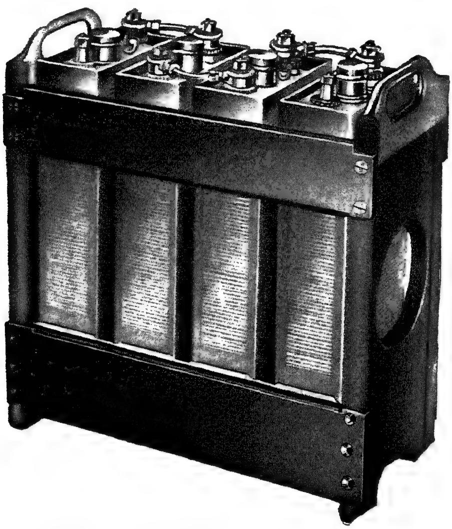


Fig. 127. Edison Cells mounted in Crate.

batteries and electric lighting of motor-cars where batteries do not generally receive the attention necessary for keeping lead storage cells in good condition. For the same reason Edison batteries are very suitable for use in private installations where expert attendance is not procurable.

Another good feature of the Edison cell is the absence of the corrosion of the terminals owing to the electrolyte not being acid. The electrolyte is a 21 per cent. solution of potassium hydrate containing some lithium hydrate. The solution loses some strength in use, and it is recommended that the electrolyte be renewed about

once a year or after about 250 complete charges and discharges. Evaporation of electrolyte is to be made good by distilled water.

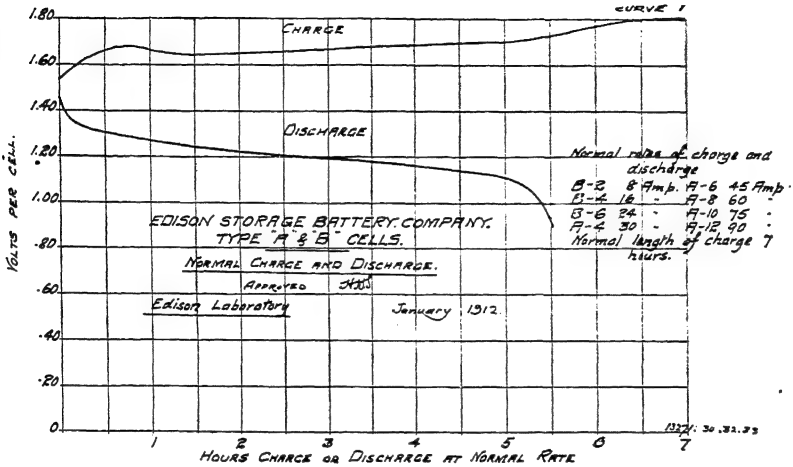


Fig. 128. Typical Charge and Discharge Curve of Edison Cell.

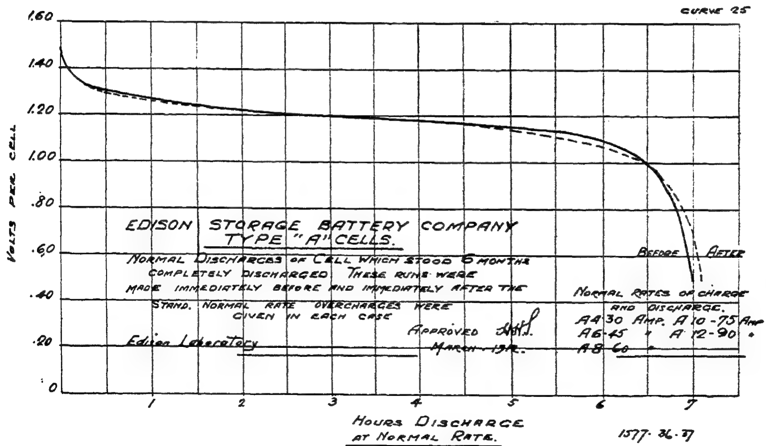


Fig. 129.

The following table gives particulars of most of the sizes of cell made at the present time (1914):

Data applying to Individual Edison Cells.

Type of Cell	B2	B4	B6	A4	A6	A8	A10	A12
Weight, in pounds	4.6	7.4	10.5	13.5	19.2	27.5	34.0	41.0
Weight, in pounds, including crate	5.5	8.7	11.8	15.0	21.0	30.3	37.5	45.0
Ampere-hour capacity—								
Rated capacity, ampere-hours	40	80	120	150	225	300	375	450
Normal actual output (7 hr. charge), amp.-hours	42	84	126	168	252	363	420	504
Maximum output on overcharge, amp.-hours	48	95	142	190	285	380	475	570
Watt-hour capacity—								
Rated capacity, watt-hours	48	96	144	180	270	360	450	540
Normal actual output (7 hr. charge), watt-hours	50.4	101	151	202	302	403	504	605
Maximum output on overcharge, watt-hours	57.0	114	171	228	342	456	570	684
Output per pound of cell—								
Rated capacity per pound, watt-hours	10.4	13.0	13.7	13.3	14.1	13.1	13.2	13.2
Normal output per pound (7 hr. charge), watt-hours	11.0	13.6	14.4	15.0	15.7	14.7	14.8	14.8
Maximum output per pound, watt-hours	12.4	15.4	16.3	16.9	17.8	16.6	16.8	16.7
Discharge rates—								
Normal (5 hour) rate of discharge, amperes	8	16	24	30	45	60	75	90
Maximum rate for intermittent discharge	50	100	140	180	225	300	350	400
Watt equivalent of normal ampere rate	9.6	19.2	28.8	36	54	72	90	108
Watt equivalent of maximum ampere rate	36	72	105	133	187	249	301	352
Average voltage—								
Discharging at normal (5 hour) rate, volts	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Discharging at $\frac{1}{5}$ normal (25 hour) rate, volts	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Discharging at 5 times normal (1 hour) rate, volts	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Internal resistance—								
Mean effective internal resistance, ohms	0.012	0.006	0.004	0.003	0.002	0.0015	0.0012	0.001
Electrical efficiency—								
Normal ampere-hour efficiency, per cent.	79	79	79	79	79	79	79	79
Normal watt-hour efficiency, per cent.	60	60	60	60	60	60	60	60

Note.—*The ampere-hour capacity of an Edison cell is practically constant at all discharge rates.*

The one respect in which the Edison cell does not compare favourably with the lead storage cell is its cost. So far, the cost of the Edison battery has prevented it from being a serious competitor of the lead battery except for traction purposes in electric battery vehicles. In this class of work, with its great fluctuations of current, the desirability of cramming in short charges (boosting charges, they are called) and the mechanical vibration to which the battery is necessarily subject, the Edison battery is extensively used in spite of its greater first cost, and it is probable that it will be the means of extending this form of traction, in time to come.

Lead batteries for electrically propelled vehicles are made both lighter and more compact than stationary batteries, and the cell cases are closed in to prevent splashing of the acid.

Approximate comparative figures for batteries mounted for vehicular traction are given below.

	Lead batteries	Edison batteries
Cubic inches of space occupied per kilowatt-hour	1000	1470
Lbs. weight per kilowatt-hour	100 to 160	70 to 75
Watt-hours per lb.	10 to 6	14 to 13
First cost per kilowatt-hour	£6	£17

For traction purposes battery capacity requires to be about 8 kilowatt-hours for each ton weight of the loaded vehicle allowing for a speed of about 20 miles per hour in the lightest vehicles (1 ton) and a reduction in speed in heavier vehicles to about 6 miles per hour in those weighing 5 tons.

MISCELLANEOUS QUESTIONS ON CHAPTER VIII

94. Describe with sketches some form of secondary battery, and explain how you would ascertain the direction in which a charging current must be sent through it. Describe the tests you would make to determine whether a cell is in good order or not. (C. and G. 1913.)

95. How many cells would be required for a secondary battery of the ordinary lead type to supply 100 amperes for three hours to a 240-volt system? If you were put in charge of such a battery and told to have it in readiness, how would you find out the state of the charge and how would you charge it? (C. and G. 1913.)

96. What do you understand by the terms: "atom," "molecule," and "valency," respectively? Make your meaning clear by illustrative examples. (C. and G. 1913.)

97. If one ampere-hour deposits 1.186 grammes of copper from a copper sulphate bath, how much will be deposited by a current of 25 amperes in $2\frac{3}{4}$ hours? How much silver would be deposited in a silver bath in the same time? (The atomic weight of silver is 108, and that of copper is 63.5.) (C. and G. 1913.)

98. If you were required to deposit silver upon an earthenware teapot, how would you proceed to do so? (C. and G. 1913.)

99. Describe in detail the erection and first charge of an accumulator, including method of handling the cells, filling with acid, connecting together, and tests for state of charge. Should the battery room be ventilated? If so, why? (C. and G. 1912.)

100. What do Faraday's Laws of Electrolysis teach you? Explain how you would satisfy yourself as to the truth of any one of them. (C. and G. 1912.)

101. Describe the construction, action and use of a Leclanché cell, and explain why the zinc rod sometimes wears away very rapidly and becomes coated with a white deposit. What is the remedy? (C. and G. 1911.)

102. Describe some form of automatic accumulator switch which will close a battery circuit when the dynamo voltage is high enough for charging and will open the circuit when the dynamo voltage falls below that of the battery. Explain clearly the principle of its action. (C. and G. 1911.)

103. Describe the construction of a secondary cell, and explain the chemical and electrical changes which occur during charge and discharge. (C and G. 1911.)

104. Define the term "capacity" as applied to a battery of storage cells. How is the capacity affected by the rate of discharge? What do you understand by the term "sulphating"? How is it caused and how is it remedied? (C. and G. 1911.)

CHAPTER IX

ELECTRIC LIGHT

There is no lack of variety of artificial illuminants, but their employment is determined chiefly by considerations of cost. The choice of an illuminant is largely in the hands of the individual user, and most people as a matter of fact attach prime importance to the question of cost; safety, convenience and adaptability are secondary matters, and hygienic considerations can scarcely be said to receive attention at all from the great majority of people. The general discussion of lighting questions is beyond the scope of the present volume, but it is necessary to point out that the invention of new types of lamps is due more to the demand for economy than to any dissatisfaction with the character of the older forms.

We do not propose dealing with other than electric lights in this volume, but before treating of electric lamps themselves it is necessary to explain how electrical energy is measured.

Energy.

Energy is the power of doing work, and is measured by the amount of work that can be done by it. When a force displaces a body, it is said to do work, and the work done is proportional to the amount of the force and to the amount of the displacement (measured along the direction of the force). In the case when a body is raised by force against the action of gravity alone (*i.e.* when there is no friction or other forces also at work) the upward force is equal to the weight of the body and the displacement along the direction of the force is the (vertical) height through which the body is moved, and the work done can be—and is as a matter of fact—measured by the product of the weight of the body and the vertical distance through which it is raised. Thus, if a weight of 7 lb. is raised through a height of 10 feet, the work done

is 70 foot-pounds. The mechanical engineer frequently specifies work in this way, viz., in foot-pounds.

In the case of electricity, we have seen (page 8) that difference of potential corresponds to difference of level in the case of fluids under the action of gravity, and we can therefore infer that the work done in sending a current of electricity along a conductor can be measured by the product of the difference of potential (E.M.F.) and the quantity of electricity which is transmitted. When the difference of potential (E) is stated in volts and the quantity of electricity (Q) in coulombs, their product (EQ) measures the work done (*i.e.* the energy expended) in joules, the joule being one of the various units used in the measurement of work or energy. A joule represents 10^7 (ten million) ergs, the erg being the C.G.S. unit of work; 1 foot-pound is equal to 1.356 joules.

Activity.

In electrical work one is frequently concerned more with the rate at which work is done than with the actual amount of work itself. Rate of working is sometimes referred to as activity, and another term used for it is power. The mechanical engineer generally specifies rate of working or activity or power in terms of the horse-power, which is defined to be 33 000 foot-pounds per minute. The electrical unit of rate of working or power in common use is the watt, which is defined as 1 joule per second. The number of watts in any case represents the number of joules per second. (1 horse-power = 746 watts, practically $\frac{3}{4}$ kilowatt.)

Suppose that in a given circuit, Q coulombs of electricity are transmitted in t seconds at a difference of potential E volts, then EQ gives the number of joules expended and $\frac{EQ}{t}$ gives the number of watts; but $\frac{Q}{t}$ is the amount of the current in amperes (call it I) so that the number of watts $= \frac{EQ}{t} = E\frac{Q}{t} = EI =$ the product of the number of volts and the number of amperes. The following equations in which the number of watts is represented by the symbol P give various forms of the foregoing relation.

$$P = EI = I^2R = \frac{E^2}{R}.$$

Board of Trade Unit.

In any given case the rate of working multiplied by the time also gives a measure of the work done (thus $EIt = E\frac{Q}{t}t = EQ$); hence work may also be specified in horse-power-hours, watt-seconds, watt-hours, kilowatt-hours. The supply of electrical energy to consumers is measured in Board of Trade Units, one Board of Trade Unit being 1000 watt-hours or 1 kilowatt-hour.

(It is necessary to point out that the Board of Trade Unit is a unit of energy and is not a unit of quantity of electricity in the sense that the coulomb is.)

Heat is also a form of energy, and it is possible to measure energy or work in terms of heat units. There are two units of heat in common use, viz., the calorie and the British Thermal Unit. The calorie is now defined as the heat equivalent of 4.2 joules; this is the amount of heat required to raise the temperature of 1 gramme of pure water from 5° C. to 6° C. on the temperature scale of the Tonnelot standard thermometer. The British Thermal Unit is defined as the amount of heat required to raise the temperature of 1 pound of water 1° Fahr.; so far, the particular degree and the type of thermometer used to measure it have not been specified in any definition of the British Thermal Unit, so that it is not possible to state its value in terms of other energy units with much precision, but it is roughly equivalent to 250 calories. The relations between the various energy and power units mentioned are set forth in the following tables:

One Board of Trade Unit (of Electrical Energy)

= 1 kilowatt-hour,

= 1000 watt-hours,

= 3 600 000 joules,

= 36 000 000 000 000 ergs,

= 1.341 horse-power-hours (practically $1\frac{1}{3}$),

= 2 655 000 foot-pounds,

= 857 000 calories,

(= 3 400 British Thermal Units.)

One Horse-power
= 550 foot-pounds per second,
= 33 000 foot-pounds per minute,
= 746 watts (practically $\frac{3}{4}$ of a kilowatt),
= 746 joules per second,
= 7 460 000 000 ergs per second,
= 177.6 calories per second,
= .746 Board of Trade Unit per hour,
(= .7 British Thermal Unit per second),
(= 42 British Thermal Units per minute).

Electric Lamps.

Electric lamps belong to one or other of three great classes :

(1) Incandescent lamps.
(2) Arc lamps.
(3) Vapour lamps.

The incandescent lamp * consists essentially of a filament of some solid conducting material which is made to give out light by having its temperature raised to a white heat owing to the passage of the current of electricity through it. The rate at which heat is developed is proportional to the square of the current and the resistance (I^2R), and the temperature reached by the filament depends upon the rate at which heat is produced and the extent and nature of the surface of the filament. With the exception of the Nernst lamp all incandescent lamps have their filaments enclosed in sealed glass globes, and with the further exception of the Half-Watt lamp these globes are evacuated to the utmost extent so as to reduce the waste of energy that would otherwise take place by convexion currents carrying off heat from the filament. The efficiency of incandescent lamps depends chiefly upon the temperature of the filament, being greater the higher the temperature.

* It has been proposed to substitute the term "glow lamp" for incandescent electric lamp, in order to distinguish it clearly from the incandescent *gas* lamp ; see the *Journal of the Institution of Electrical Engineers*, Vol. 52, page 599. This innovation has not been adopted in the present volume.

It is obvious that no incandescent lamp can be worked with its filament at a temperature as high as its melting-point, but before even this temperature is reached evaporation begins to take place from the surface of the filament. This is the cause of the blackening of the bulbs of incandescent electric lamps which is effected by the condensation of the evaporated molecules on the comparatively cold glass of the bulb.

Vapour lamps employ some vapour or gas as their working substance. This is enclosed in a long glass tube, and the current is admitted at one end and taken out at the other by wires sealed into the ends of the tube. As a rule, vapour lamps can be designed for very high efficiency owing to the fact that when a vapour or gas is heated to incandescence the light given out does not depend primarily on the temperature alone. Vapours have what is called a selective power in respect of the radiations which they emit, and by choosing vapours with a large proportion of visible light among their radiation high efficiency from the lighting point of view is obtained. The chief defect to which vapour lamps are liable arises from this very cause, viz., the predominance of some one colour in the light emitted.

Arc Lamps.

The arc light is formed by sending a current of electricity through two conductors placed in contact and slowly separating them. Just at the moment of their parting contact a high temperature is produced at the point of contact owing to the large resistance at that place, and the formation of vapour serves to maintain the continuity of the circuit after the conductors have parted. The length to which the arc may be produced depends upon the amount of the current and the rapidity with which the vapour is oxidised by the oxygen in the atmosphere.

It will be obvious that the arc light combines the features of the incandescent lamp and the vapour lamp, the light from it coming partly from the incandescent ends of the conductors forming the arc and partly from the stream of incandescent vapour; it is the latter which accounts for the colour tint of arc lights. In an ordinary arc lamp the stream of vapour contributes about

5 per cent. of the total light given out. Under any circumstances the efficiency of the arc light will depend greatly on the temperature of the incandescent ends of the conductors forming the arc, and for this reason carbon rods are always employed.

The carbon arc light was discovered in 1802 by Professor Ritter, soon after the discovery of the voltaic pile, and the experiments of Sir Humphry Davy in 1808 revealed its principal features. Carbons of wood charcoal were originally used, but as these were rapidly consumed the use of retort carbon was introduced by Foucault in 1843. In 1877 Siemens introduced cored carbons. Modern carbons are made from finely ground evenly graded mixtures of graphite and carbon moistened with tar, treacle or sugar solution; this is forced through circular dies and then baked with a high temperature in earthenware vessels from which the air is excluded; the carbon tubes thus produced have their cores filled with a softer material (graphite or graphite with added chemicals) which is forced into them; then they are thoroughly dried.

The passage of electricity through the electric arc is somewhat similar to the conduction of electricity through an electrolyte. The vapour of the arc consists of a stream of carbon atoms which leave the positive carbon taking with them charges of positive electricity. Those which are not oxidised by the way reach the negative carbon. This explains why the positive carbon is consumed at a greater rate (about twice) than the negative carbon *, and also accounts for the formation of a crater on the former and the more or less pointed shape assumed by the latter. Of course, oxidation takes place at the heated ends of the carbons as well as along the exposed sides of the stream of vapour, and the advantage of cored carbons lies in their facilitating the maintenance of a regular shape at the burning ends.

The oxidation of the vapour in the arc has the effect of giving it a sort of waist-like shape, and the constriction varies not only with the length of the arc but also with the amount of the current. As a consequence the apparent resistance of the arc diminishes as the current increases, and it is necessary to employ an external

* In some lamps a thicker carbon is used for the positive, in order that positive and negative carbons may burn with the same rate of change of length.

resistance in series with the arc in order to maintain it in a stable condition.

It will be obvious that an arc light requires a glass globe or some kind of enclosure to shield it from draughts if a steady light is to be obtained. However, it is impracticable to seal up an arc lamp so as to completely exclude access of air, as the carbon vapour would soon cover the globe with a sooty deposit.

Arc lights controlled and regulated by hand are often used for lantern work, but for ordinary lighting the arc lamp has to be provided with mechanism for automatically performing the various adjustments. Such mechanism is required to perform the following operations:

(1) to bring the two carbons together when no current is passing through the lamp, in order to be ready for action when the current is switched on;

(2) to "strike" the arc, that is, to separate the carbons to the proper distance when the current is switched on;

(3) to "feed" the arc, that is, to make the carbons approach as required to compensate for the carbon consumed during burning.

Operation (1) is generally effected by arranging the mechanism so that the carbons are brought together by the action of their weight when no current is passing. The striking of the arc is always produced by means of the action of a series coil on a soft iron core. The position of the core is so arranged that when it is magnetised by a current in the coil the magnetic attraction between them tends to lift the core, and when the amount of the current is sufficient the core is lifted and its motion is communicated to the carbons in such a way as to part them, thus striking the arc. The feeding of the arc is generally accomplished by means depending on the use of a shunt coil—in addition to the foregoing—which consists of a large number of turns of fine wire connected between the two carbons. Fig. 130 gives a skeleton diagram of connections of an arc lamp.

The various makes of arc lamp differ chiefly in the details of mechanism. The working of arc-lamp mechanism is best studied from the actual lamp itself, but the following particulars of the working of the well-known Crompton arc lamp may help to give the student an idea of some of the devices employed.

Fig. 131 gives a diagrammatic view of the principal parts of the Crompton arc-lamp mechanism. The carbons are suspended by flexible cords worked by a drum *D* so that they approach or recede according to the direction of rotation of the drum. The drum is secured to the same shaft as a brake wheel *W*, the motion of which is regulated by the friction of a band *B*, one end of which

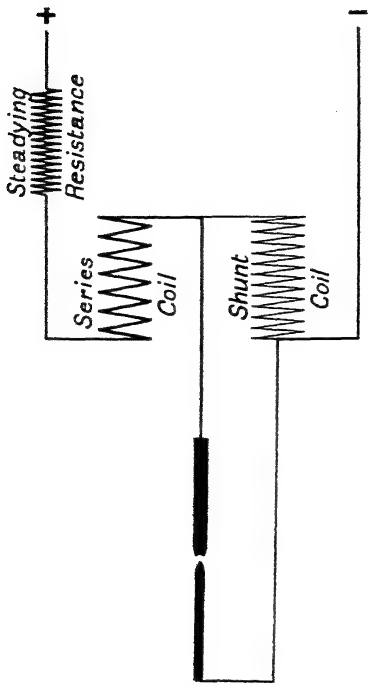


Fig. 130. Diagram of Arc Lamp Connections.

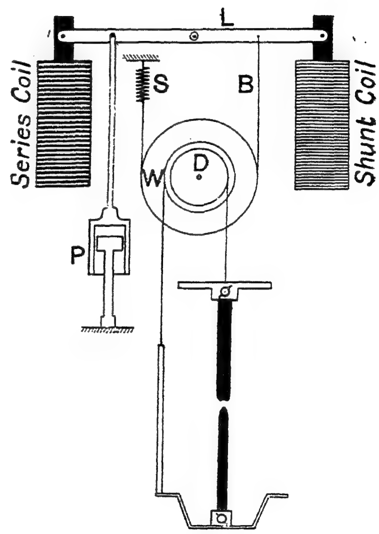


Fig. 131. Diagram of Crompton Arc Lamp Mechanism.

is secured to a fixed point by a flexible spring *S* and the other end is attached to a rocking lever *L*. The motion of the rocking lever *L* is regulated by the relative pulls upon the soft iron cores of the series and shunt coils, and everything is so adjusted that when no current is passing through the lamp, the friction of the band *B* on the wheel *W* is just insufficient to prevent the carbons moving into contact owing to the greater weight of the upper carbon and its holder. The carbons therefore come into contact

when the current is turned off. When the current is turned on the shunt coil is short-circuited for the moment and the current in the series coil tilts the lever L which pulls the band B, thus both tightening its grip on the wheel W and rotating the wheel to an extent sufficient to strike the arc. Thereafter the friction of the band B is regulated by the relative proportions of the currents in the series and shunt coils, any increase of current in the shunt coil (such as may be due to the consumption of the carbons) tending to ease the friction on the wheel W and allow the carbons to feed through the action of their weight.

A dash-pot P is provided to prevent violent oscillation of the rocking lever L. This consists of a hollow cylinder and plunger the relative motion of which is actuated by the rocking lever. The friction of the air retards their relative motion with a force depending on the rate of motion but without affecting the position of balance of the lever; it therefore has a steadying effect on the lever without disturbing its adjustment by the forces produced by the currents in the shunt and series coils. (The principle of this action has been described in another connection on page 68.)

Types of Arc Lamps.

Up till recent years the only kind of arc lamp made was what is now called the open type. In this type pure carbons are used, and the air has free access to the arc. Usually the carbons are placed in vertical alignment. Open arc lamps are only suitable for a voltage of about 50 to 60; on circuits of higher voltage they must be run with two or more in series according to the voltage of supply. They can be made to take any current from 5 amperes upwards, though they are seldom made for less than 10 amperes. Their efficiency is about 2 candle-power per watt.

About the end of last century the enclosed arc was invented. Its essential difference from the open arc consists in its having the globe (or the inner one of two globes) so closely fitted as to limit the access of air to the amount necessary to oxidise stray particles of carbon vapour. This arrangement enabled the stream of vapour to be maintained at a fairly uniform width, and several advantages followed in consequence, viz.:

(1) longer arcs could be employed, thus allowing lamps to be constructed for running singly on higher voltages;

(2) thinner carbons might be employed, thus allowing lamps to be constructed for smaller currents;

(3) carbons were not consumed at so rapid a rate;

(4) simpler mechanism owing to being able to dispense with *special* arrangements for feeding the arc.

Enclosed arcs were always made with carbons in vertical alignment, and sometimes they were made with "twin" arcs, that is, two arcs side by side in the same lamp. In one form or another, it was possible to make enclosed arcs for all ordinary lighting voltages and for any current from 2 amperes upwards. Their one drawback was that their efficiency was only about half that of the ordinary open arc, which acted as a set-off against their lower first cost (due to simpler mechanism) and the less amount of attention necessary owing to the slower consumption of the carbons. Now that metal filament incandescent lamps can be obtained with practically the same efficiency (1 c.p. per watt), much better colour tint and requiring practically no attention for months, the enclosed arc lamp will soon become obsolete.

The most important development in arc lamps has been the production of the flame arc. The ordinary arc light has a blue tint, and the flame arc is the practical outcome of the endeavour to improve the colour of the arc by adding ingredients to the carbon which would produce vapours emitting a large proportion of red or yellow light. Flame arcs are simply open arcs using carbons with cores impregnated with calcium or other salts and having their mechanism modified to suit the much more rapid consumption of carbons which this entails. Modern makes have a "magazine" of carbons which are automatically brought into action in turn so as to save too frequent renewals of the supply of carbons.

Flame arcs work at about the same voltages as ordinary open arcs, but they have much greater efficiency; in fact, they are the most efficient lamps which have been produced so far, giving about 7 candle-power per watt.

Carbon Filament Incandescent Lamps.

The principles applied in the construction of incandescent electric lamps were quite well understood as long ago as 1836, but their practical development had to wait until the invention of the dynamo enabled electricity to be produced in quantity at reasonable cost. Lane-Fox, Maxim, Edison and Swan were among the pioneers of incandescent electric lighting. Until recent years, no metals were known with a higher melting-point than carbon, and for a long period incandescent electric lamps were made with carbon filaments only.

The chief difficulty encountered by the earlier workers was obtaining carbon filaments of sufficiently uniform cross-section. The process of "flashing" was devised to remedy the irregularities of cross-section of the filament. This process consists in fixing the filament in a holder under the glass receiver of an air pump; the air is exhausted and benzine vapour is admitted; a current of electricity is sent through the filament. The thinner parts of the filament reach a higher temperature than the thicker parts, and the benzine vapour in the neighbourhood of the filament is decomposed into carbon and hydrogen at a rate depending on the temperature. The carbon adheres to the filament and the hydrogen is carried away by the air pump. The result of the operation is to coat the whole filament with fresh carbon, but the parts which were originally thinnest get the thickest deposit of fresh carbon, and a very nearly uniform filament can be produced in this way. The operation is stopped when the filament reaches the required thickness, which is determined by some easy form of resistance measurement.

Swan invented a process for producing uniform filaments of carbon from cotton thread, and for years the well-known Edison-Swan lamps had their filaments made by this process. Cotton thread was drawn through sulphuric acid at such a rate as just to gelatinise it completely, and through water to wash off any sulphuric acid. The thread was then hung up to dry, and when dried was drawn through dies to the proper cross-section—in the same way as wires are drawn. The finished thread was then wound on wooden formers of suitable size and shape and the

thread-wound formers were packed in plumbago crucibles with carbon dust (so as to prevent their burning in the next operation) and heated gradually to a white heat in a reverberatory furnace. Cotton consists of a compound (cellulose) of carbon, hydrogen and oxygen, and the heating drives off the hydrogen and oxygen (in the form of steam), leaving pure carbon. The furnace is allowed to cool slowly, and when cold the filaments are unpacked in preparation for subsequent processes.

For some years there has been used a simpler process than that of Swan. It starts with cotton wool which is dissolved in a solution of zinc chloride forming a sort of syrup, which is then drawn through a filter by an air pump and squirted through apertures of the required size into acidulated alcohol, which hardens the filaments thus formed. These are then quite uniform and after the drying process are ready for winding on formers for treatment in the furnace process.

Although flashing is no longer necessary for the production of uniform filaments, it is still used for another reason. Filaments that are not flashed blacken the bulbs of the lamps at a much more rapid rate. It appears that the flashing process yields a firmer form of carbon than that obtained in the unflashed filament.

As the filament will be eventually mounted inside an evacuated glass bulb, it is necessary to attach its ends to "leading in wires" which admit of an air-tight seal through glass. Platinum is generally used for leading in wires (and the scrap value of old lamp tops is due to the platinum they contain). The leading in wires are cut into suitable lengths and have a spiral or scoop formed on one end of each into which the end of the filament is threaded. A sound mechanical and electrical joint is then made at the junction by placing the filament and leading in wires into a clamp arranged so that a current of electricity can be passed across the joints, while the whole is immersed in benzine. This causes a firm deposit of carbon to be made over the joint in a similar manner to that described in connection with the flashing process.

The remaining processes of manufacture of incandescent electric lamps are all straightforward. Apart from testing, the process of exhausting the bulb is the last. As far as carbon filament lamps are concerned, it is also the most costly, and several

devices have been introduced from time to time to cheapen this part of the manufacture. It is necessary to add that in the interests of efficiency, the process of exhaustion must be carried very much further than is necessary merely to protect the filament from combustion. The point at the extreme end of the bulb of an incandescent lamp indicates the position of the tube through which the air was exhausted in the manufacture of the lamp.

Metal Filament Incandescent Lamps.

It is not practicable to make carbon filament lamps with higher efficiency than 0.3 candle-power per watt ($3\frac{1}{2}$ watts per c.p.), and all hope of further improvement in incandescent lamps depended upon the discovery of some conducting substance with a higher melting-point than carbon. There are many oxides with extremely high melting-points and the incandescent *gas mantle* is made of a mixture of two of these, thorium oxide and cerium oxide. The Nernst electric lamp employed a filament of the same composition which had the merit of not requiring to be mounted in an exhausted globe, but it laboured under the great disadvantage that the filament did not conduct electricity until its temperature had been raised sufficiently, and no light was obtained until this preliminary heating process had been carried out. Although the Nernst lamps were provided with automatic heaters, the public felt some diffidence about using lamps that did not light up instantly on switching on the current. In any case, the production of metal filament lamps has rendered the Nernst lamp obsolete.

The most important development in connection with the use of electricity for lighting, or indeed in the use of artificial lights of any kind, has been the production of the metal filament incandescent lamp. Several metals are now known which have a higher melting-point than carbon. All of these are not equally suitable for use in incandescent electric lamps. The first to be so used was osmium, but the osmium lamp never really established itself in a commercial sense. The next to be put on the market was the tantalum lamp with filaments of tantalum wire. Tantalum lamps are still used. Their efficiency is about half-a-candle-power per watt.

The metal now most commonly used in incandescent filament lamps is tungsten. For some time filaments of tungsten could only be made by producing the metal in the form of a fine powder which was made up into a paste, then squirted into filaments from which the other ingredients were removed by suitable subsequent treatment. Methods have been devised for producing the metal tungsten in a sufficiently ductile state to admit of its being drawn into fine wires, but it is not to be assumed that all tungsten lamps have filaments of *pure* tungsten, as it is probable that some of the processes used for the preparation of the filament yield some sort of alloy or alloy-like compound of tungsten *.

Apart from the manner in which the filament is produced, the manufacture of metal filament lamps is similar to that of carbon filament lamps, omitting such processes as flashing which are special to carbon.

The efficiency of tungsten filament lamps is practically 1 candle-power per watt. The only other kind of electric lamp which notably surpasses it in efficiency is the flame arc, and consequently the tungsten lamp is superseding all other forms of electric lamp for general use. Doubtless, there will be some special purposes for which other types of lamp will continue to be used. The flame arc still seems to have a future before it for street lighting, though that is not a matter one can be confident about, as the arc lamp appears to have been brought more nearly to the limit of its perfection than has the incandescent metal filament lamp.

Quite recently there have been produced tungsten filament incandescent lamps with an efficiency of 2 candle-power per watt, called half-watt lamps †. The special feature of such lamps is that

* Owing to an exchange of licences by the firms holding the controlling patents, and to licences granted thereunder, the following present makes of metal filament lamps sold in the United Kingdom are included in the Tungsten Lamp Association:

Aegma	Osram	(Tantalum)
Auriga	Phillips, "UK"	Wotan
F. (Foster)	Royal Ediswan	"Z"
Mazda	Stearn (Leuconium)	

† For particulars of the Mazda Half-Watt Lamp, see *Electrician*, Vol. 71, page 864, Aug. 1913.

For particulars of the A.E.G. Nitra Lamp, see *Electrician*, Vol. 72, page 320, Nov. 1913.

the bulb contains nitrogen gas at a pressure of something below 1 atmosphere and the filament is so arranged that the convection currents set up in the nitrogen carry the evaporated particles from the filament upwards and deposit them on the upper part of the bulb, where their interference with the emission of the light is comparatively small. The half-watt lamp has a much longer neck than ordinary lamps. The long neck not only serves the purpose of receiving the deposit of particles but also prevents an excessive amount of heat from reaching the metal cap of the lamp. Where the long neck joins the bulb a mica disc is fitted to keep the heated nitrogen from impinging direct upon the sealing tube, so as to remove the risk of cracking it.

The arrangement for removing the deposit from the lower part of the bulb enables the lamp to be run with the filament at a higher temperature than the ordinary type of lamp without increasing the rate at which light is cut off by the blackening of the bulb. The increase in the efficiency is due to the higher temperature of the filament in accordance with the principle mentioned on page 212.

The candle-power of the half-watt lamp falls to about 15 % below its initial value after 1000 hours of burning, and 800 to 1000 hours is found to be the average useful life of the lamp *.

Illumination.

The illumination produced by a lamp diminishes as the distance from it increases; in fact, it varies inversely as the square of the distance. Illumination is measured in foot-candles, one foot-candle being the illumination produced by one candle-power at a distance of one foot (or 4 c.p. at 2 ft., 9 c.p. at 3 ft. and so on).

At the present time half-watt lamps are obtainable in the following sizes:

Voltage	Watts	Approximate over-all dimensions
50 to 130	300 to 500	12 ″ × 6″
100 to 130	1000 to 1500	12½″ × 7″
200 to 260	1000 to 1500	14½″ × 8″

* Particulars of recent tests on half-watt lamps are given in the *Electrician* Vol. 73, p. 800 (Aug. 1914).

Number of foot-candles = candle-power ÷ (distance in feet)^2.

In the days when candles, paraffin lamps or batswing gas burners supplied the only artificial light available, only small candle-powers could be used and good illumination had to be secured by working in close proximity to the lamp. With illuminants of such small "intrinsic brilliancy" it was not particularly necessary to take special precautions to screen the source of light from the direct vision of the eye, but with modern lamps—especially electric lamps—it is essential to arrange matters so that the eye does not view the incandescent substance directly from close range. When small lamps are used at close quarters, shades or such appliances should be used and in such a manner as to screen the eye.

The iris of the eye automatically adjusts its aperture to give the clearest vision with the illumination provided; the smaller the illumination the larger the aperture. Nocturnal animals such as cats, bats, owls, have eyes constructed so that their irises can produce comparatively large apertures—beyond the limits of the human eye for example—and they thus are capable of better vision in semi-darkness. (They cannot see in absolute darkness as is sometimes supposed.) At the same time, vision is not nearly so good with a large aperture and small illumination as it is with great illumination and a small aperture (although it is better than can be obtained with small illumination and a small aperture). The human eye is constructed for illuminations approaching that of moderately good diffused daylight. Diffused daylight ranges from about 10 foot-candles to 40 foot-candles and the best illumination for the human eye is about 10 to 15 foot-candles, but up to the present it is only for such fine work as surgical operations and engraving that illuminations of 10 or more foot-candles have been arranged for by artificial lighting. For ordinary use it is usual to design for 2 or 2½ foot-candles.

A very much more serious defect than the employment of too small illumination is to place lamps near the line of the eye. Any observant person will have noticed that in a room with lamps only some 7 to 9 feet above the floor, the lamps frequently attract the gaze of the occupants. On looking at a bright source of light the aperture of the eye contracts beyond the best adjustment

for the general illumination and where lamps readily meet the eye, the vision cannot be maintained at its best. The ideal thing for ordinary rooms is "indirect lighting," that is to cover the lamps from direct vision either by reflectors placed below them or by placing them behind a cornice and lighting the room by the light diffused from the ceiling (and perhaps also the upper parts of the walls). Where economy demands a less expenditure of energy than is required for indirect or semi-indirect lighting the next best thing is to place the lamps close up to the ceiling or at any rate well above the line of the eye. The smaller direct illumination produced by so doing is partly compensated for by the better supply of diffused light and is generally more than compensated for by the improvement in the conditions for the eyesight.

It is a common mistake to suppose that artificial light is necessarily hurtful to the eyesight or that it is better to employ small artificial illumination. The hurtful thing is looking direct at the incandescent source of the light. Indeed, daylight is open to the same objection; in fact, it is positively dangerous to look direct at the sun.

Lighting with incandescent electric lamps can often be considerably improved by the wise use of shades, but some discrimination is necessary to obtain the best results, especially with focussing types of shades. For reading purposes, the judicious use of shades will generally effect economy in the consumption of electricity but for most kinds of hand-work the use of shades is not advantageous owing to the sharpness of the shadows cast and the darkness of surfaces not exposed to the direct rays. Incandescent electric lighting has an adaptability not possessed by any other form of lighting.

Cost of Electric Lighting.

Lighting costs may be classified under the following three heads:

(1) Cost of installation;

(2) Cost of maintenance and repairs;

(3) Consumption costs.

We cannot enter here into a full discussion of questions of costs but we may point out certain principles involved in the estimation of such costs in so far as electric lighting is concerned.

As regards a private house installation taking its supply of electricity from a Supply Company or a Corporation, there is little to be said as to the cost of installation which would include wiring and fittings. The amount spent upon these would generally depend more upon the individual taste of the consumer than upon the lighting requirements of the house and would be but little affected by the choice of lamps. In such a case, we may limit ourselves to the discussion of the relative cost for electricity and lamp renewals of the various types of incandescent electric lamp.

It is obvious that the consumption of electricity will vary in proportion to the efficiency of the lamps used and, at first sight, it might be supposed that the frequency of renewals would simply depend upon the time that the lamps would run before the filaments broke. However, it does not always pay to keep a lamp going so long owing to the loss of light occasioned by the deposit on the bulb. For example, a 32-c.p. carbon filament lamp taking 100 to 120 watts (according to the efficiency used) would in the course of time (300 to 800 hours of burning) be giving only 25 candle-power. To continue such a lamp in use after that stage had been reached would be no better from the lighting point of view than to substitute for it a new 25-c.p. lamp. The latter would cost say 1*s.* which would not be incurred by retaining the old lamp but it would take 20 watts less, thereby saving one Unit (kilowatt-hour) for every 50 hours of burning. In the next 400 hours of burning it would save

1*s.* 4*d.*	worth of electricity	with electricity	costing	2*d.*	per	Unit,
2*s.*	,,	,,	,,	3*d.*	,,	,,
2*s.* 8*d.*	,,	,,	,,	4*d.*	,,	,,
3*s.* 4*d.*	,,	,,	,,	5*d.*	,,	,,

thus effecting a net saving compared with the original 32 c.p. at these charges.

It will also be noticed that the dearer electricity is, the less time it takes for the new lamp to save its first cost. The higher the price of electricity is, the more important does it become

to secure efficiency in the lamps, even at the expense of more frequent renewals.

The above example is only given for purposes of illustration. As a matter of fact, it does not pay to keep lamps going after the candle-power falls below 80 per cent. of the normal. The "useful life" of an incandescent lamp is defined as the number of hours of burning in which the candle-power reaches 80 per cent. of the initial candle-power.

When an incandescent electric lamp is put into use, the candle-power increases for a time owing to changes in the molecular state of the filament, but afterwards the candle-power begins to fall off more or less steadily owing to the growth of the deposit on the bulb. It is obvious that the rate at which the deposit forms will depend on the dimensions of the bulb, the dimensions and the arrangement of the filament and the temperature of the filament (that is, upon the efficiency of the lamp). As is to be expected therefore, the candle-power falls at a more rapid rate in high voltage lamps (200 V. to 250 V.) than in low voltage lamps (100 V. to 120 V.) and in small candle-power lamps than in large candle-power lamps.

The useful life of carbon filament lamps ranges from 300 hours to 800 hours with filaments run at 3 to $3\frac{3}{4}$ watts per c.p. for low voltage lamps and $3\frac{1}{2}$ to $4\frac{1}{2}$ watts per c.p. for high voltage lamps. The most commonly used sizes are the 8 c.p., 16 c.p., 32 c.p., and the retail prices are from 9*d.* to 1*s.* 2*d.* each, according to the size and quality.

At one time the life of tungsten filament lamps was conditioned solely by the breaking of the filament and even now when their manufacture has so improved that it is quite common for their filaments to last for more than 2000 burning hours, it is seldom necessary for them to be renewed before the filament gives out. The candle-power of tungsten lamps shows a marked increase during the early hours of use and when they are run at from $1\frac{1}{4}$ watts per c.p. in the smaller sizes to 1.1 watts per c.p. in larger sizes, the candle-power falls little, if any, below the initial amount in the first 1000 hours of burning and it seldom reaches the 80 % value in 2000 hours.

The sizes of tungsten lamps are arranged according to the

watts taken. The prices* and approximate candle-powers of the usual stock sizes are as follows:

	100 V. to 135 V.		200 V. to 260 V.	
Watts	C.p.	Price	C.p.	Price
		s. *d.*		*s.* *d.*
10	8	2 2		
15	12	2 2		
20	16	2 2	14	2 11
30	25	2 2	22	2 8
40	33	2 2	30	2 8
60	50	2 2	48	2 8
80	67	4 2	64	4 2

100 V. to 260 V.

Watts	C.p.	Price *s.* *d.*
100	90	4 3
200	180	8 6
300	270	16 0
400	360	16 0
600	540	20 0

Lamps under 100 watts are made either with pear-shaped or round bulbs. The prices given are for pear-shaped bulbs; lamps with round bulbs cost 3*d.* more each. Lamps of 100 watts and over are only made with round bulbs.

Tungsten lamps are made in a number of stock sizes ranging from 5 to 60 watts for voltages between 20 and 85 such as are met with in connection with motor-car lighting, houses with transformers and some private installations. The price of lamps for these very low voltages ranges from 2*s.* 1*d.* to 3*s.* 6*d.* according to size and voltage.

Now that tungsten lamps can be relied upon to give an average life of over 1000 hours, they are indisputably the most economical electric lamps for indoor use and many problems connected with comparative costs have ceased to be matters of practical consequence.

For purposes of illustration we give below a statement showing the costs† per 1000 hours of burning of a low efficiency 32-c.p.

* Prices given in this chapter may be taken as correct for July 1914. The market has suffered some disturbance since then.

† It is obvious from what has already been said with regard to the performances of incandescent electric lamps that very precise calculations of costs are not warranted by any available data and round numbers are all that can be justified. The figures in the statement are given with undue refinement but this is done deliberately so as not to confuse the student in following them.

carbon filament lamp, a high efficiency 32-c.p. carbon filament lamp and a 40-watt tungsten lamp, all for low voltages. (The initial candle-power of a 40-watt tungsten lamp is practically 33 c.p. for low voltage lamps and 30 c.p. for high voltage lamps, but either of these would give a rather better average candle-power than a 32-c.p. carbon filament lamp; low voltage carbon filament lamps can be run at about 20 per cent. higher efficiency for the same useful life than high voltage ones; hence a similar statement for high voltage lamps would place the tungsten lamp in a still more favourable relative position.)

	Low efficiency carbon filament lamp	High efficiency carbon filament lamp	40-watt tungsten filament lamp
Watts per initial candle-power ..	3.5	3.1	1.2
Watts	114	99	40
B. of T. Units consumed in 1000 hours of burning	114	99	40
Consumption costs per 1000 hours of burning:			
At ½*d.* per Unit	4/9	4/1	1/8
" 4*d.* "	38/–	33/–	13/4
" 6*d.* "	57/–	49/6	20/–
Useful life (hours)	800	400	1000
Renewals per 1000 hours of burning ..	1¼	2½	1
Price per lamp	1/–	1/–	2/2
Cost of renewals per 1000 hours of burning	1/3	2/6	2/2
Total cost per 1000 hours of burning:			
At ½*d.* per Unit	6/–	6/7	3/10
" 4*d.* "	39/3	35/6	15/6
" 6*d.* "	58/3	52/–	22/2

If the above statement had also included an equivalent metallised-carbon filament lamp and tantalum lamp, their costs would have worked out at something intermediate between that of the high efficiency carbon and the tungsten.

It will be observed that the dearer electricity is, the greater the advantage in using tungsten lamps. The charges per Unit at which the costs have been worked out have been chosen for the following reasons: the charges for electricity for lighting of most public supplies in this country come within a fraction of 4*d.* per Unit; 6*d.* per Unit is about the highest rate charged;

$\frac{1}{2}d.$ per Unit is practically the lowest figure at which electricity can be produced in England.

Large consumers purchasing lamps by the thousand are able to obtain liberal discounts from the prices quoted, thus reducing the cost of renewals. It may be pointed out that the effect of this is to give a further comparative advantage to the tungsten lamp.

The items entering into the costs of lighting with arc lamps are:

(*a*) First cost of the lamps; cost of repairs;

(*b*) Cost of carbons consumed;

(*c*) Cost of labour employed in cleaning lamps and fitting fresh carbons;

(*d*) Cost of electricity consumed.

The cost of obtaining a given amount of candle-power hours by means of arc lamps depends upon the sizes of lamps employed as well as upon the type, but as far as the type of lamp is concerned, enclosed arcs, open arcs, flame arcs represent the order of the costliness of items (*a*), (*b*) and (*c*), while the reverse order applies to the costs of item (*d*).

The price of enclosed arc lamps is generally between £2 and £3 each, varying according to size and make; open arc lamps are generally about £5 each; the prices of flame arc lamps range from £7 to £11 according to the make, the magazine arrangements affecting the price.

Most arc lamps are now made to work with 12-inch carbons. The rate of consumption of carbons is about $1\frac{1}{4}$ inches per carbon per hour ($=2\frac{1}{2}$ inches of carbon altogether) in flame arcs, rather less in ordinary open arcs and about $\frac{1}{4}$ inch per carbon per hour in enclosed arcs. The price of carbons depends very much upon the diameter (which depends upon the current for which the lamp is designed) and the quantity purchased at a time as well as quality, and flame carbons are dearer than plain carbons. Plain carbons suitable for a 10-ampere open arc may be obtained for 4*d.* per pair, 25*s.* per 100 pairs and £10 per 1000 pairs. The cost of carbons consumed in lamps of the same wattage is about one-sixth for enclosed arcs of its amount for ordinary open arcs

and in flame arcs it is from 3 to 5 times the amount for ordinary open arcs.

As regards the labour of cleaning arc lamps and fitting fresh carbons, in private installations the trouble connected therewith would generally be more objectionable than the cost.

Street Lighting.

In the lighting of streets the distribution of the light is a matter of the first importance and in this case it is useless to work out comparative costs on the basis of the total light emitted. As a rule, in street lighting it is the minimum illumination to which attention is directed but sometimes regard is also had to the average illumination. Arc lamps—and especially flame arc lamps designed for street lighting—have an advantage over incandescent lamps for this purpose in respect of the fact that they send their maximum candle-power in an oblique downward direction. No lamp has a uniform distribution of light in all directions; incandescent lamps usually send out their greatest candle-power in a horizontal direction; this is not generally a disadvantage for indoor lighting but for street lighting it renders the use of suitable shades or reflectors imperative in order to obtain the best results.

MISCELLANEOUS QUESTIONS ON CHAPTER IX.

105. What is the current in a 180-watt 220-volt lamp when switched on to a 220-volt supply?

Answer. Number of watts = number of volts × number of amperes, hence
number of amps. = number of watts ÷ number of volts,
,, ,, $= 180 \div 220$,
,, ,, $= .82$.

The required current is .82 amperes.

106. An electric heater is to be made to take 1500 watts on 230 volts. What must its resistance be?

Answer. Number of watts = (number of volts)^2 ÷ number of ohms, hence
number of ohms = (number of volts)^2 ÷ number of watts,
,, ,, $= \frac{230^2}{1500} = \frac{230 \times 230}{1500} = 35.2.$

The resistance of the heater should be 35 ohms.

107. How many units will be consumed in 2000 hours by a 30-watt lamp ?

Answer. In 2000 hours a 30-watt lamp will take 30×2000 watt-hours or $\frac{30 \times 2000}{1000}$ kilowatt-hours, that is 60 kilowatt-hours, that is 60 Board of Trade Units.

108. What is the average current supplied to a consumer on a 230-volt supply who uses 106 units in 24 hours ?

Answer. 106 units in 24 hours $= 4.42$ units per hour.

A unit per hour means 1000 watts, so that the consumer is taking an average of 4.42 times 1000 watts, that is 4420 watts.

4420 watts at 230 volts represents a current of $\frac{4420}{230}$ amperes (see No. 105 above), so that the consumer's average current is 19.2 amperes.

109. How long will one B. of T. unit keep a 16-c.p. lamp going if the lamp takes 3.75 watts per candle-power ?

Answer. 16 candle-power at 3.75 watts per c.p. takes 16×3.75 watts or 60 watts. One Board of Trade unit is 1000 watt-hours, and can therefore supply 60 watts for $\frac{1000}{60}$ hours, that is for 16 hours 40 minutes.

110. What must be the brake horse-power of the engine driving a dynamo giving 150 amperes at 240 volts, with an efficiency of 93 % ?

Answer. Output of dynamo $= 240 \times 150$ watts $= 36\,000$ watts $= 36$ kilowatts, hence horse-power converted $= \frac{4}{3}$ of $36 = 48$. This represents 93/100 of the horse-power required, so that horse-power of engine $= 48 \times 100 \div 93 = 51\frac{1}{2}$.

111. Find the number of watts dissipated in sending a current of 25 amperes through a resistance of 1.2 ohms.

Answer. 750.

112. How long will each of the following lamps take to consume one Board of Trade Unit ?

(*a*) A 32-c.p 120-watt carbon filament lamp.
(*b*) A 23-c.p. 110-volt .35-amp. tantalum lamp.
(*c*) A 30-c.p. 40-watt osram lamp.
(*d*) A 2.3-amp. 220-volt enclosed arc lamp.
(*e*) An 850-c.p. 110-volt $3\frac{1}{2}$-amp. Westinghouse mercury vapour lamp.

113. How many hours can a 60-watt lamp be kept lit at a cost of 1*d*. when electricity is 4*d*. per unit ?

114. Give a practical definition of the following terms and state their relationship to each other : "volt," "ampere," "ohm," "watt," "coulomb," "calorie," "volt-ampere," "ampere-hour," "watt-hour," "Board of Trade Unit." (C. and G. 1913.)

115. Calculate the current in, and the resistance of, a circuit which absorbs 550 watts at 110 volts. (C. and G. 912.)

116. Two coils, connected in parallel, take a total current of 10 amperes at 230 volts from the supply mains. If the power absorbed by one coil is 950 watts, what is its resistance and what is the resistance of the other coil? (C. and G. 1912.)

117. If a 16-c.p. 100-volt lamp consumes 35 watts, what is its resistance and what current does it take? (C. and G. 1911.)

118. An overhead transmission line consists of two wires, each 2 kilometres long and 150 square millimetres cross-sectional area. If the continuous current flowing in one and returning in the other is 150 amperes, what will be the power in watts wasted in the line? The specific resistance of copper is 1.72 microhms per centimetre cube. (C. and G. 1911.)

119. Prove the law that the number of watts wasted in a resistance, when a current is supplied at a constant voltage, is inversely proportional to the resistance. An electromagnet used on a constant voltage of 30 volts has a resistance when cold of 8 ohms. After being on a circuit for half an hour the resistance has increased to 12 ohms. Find the rate at which energy is being wasted at first, and when the coil has thus warmed up. (C. and G. 1910.)

120. Describe the construction of incandescent lamps, and state approximately the relations between candle-power, watts, volts and amperes. What advantage have metal filament lamps over carbon lamps? (C. and G. 1913.

121. Describe some form of incandescent electric lamp, giving figures for volts, amperes and candle-power, and state how the resistance varies with change of temperature. (C and G. 1912.)

122. What are the chief points of difference between a flame arc lamp and an ordinary arc lamp? To what is the golden colour of the light from some flame arc lamps due? (C. and G. 1910.)

123. Mention other items that require to be considered in comparing the cost of various illuminants such as oil, gas, electricity, etc., besides the cost of the oil, gas, and electricity used.

124. On what depends the ratio of the light obtained to the energy expended in an electric lamp? Explain why it is that carbon filament lamps are not run at an efficiency much higher than 1 candle-power for $3\frac{1}{2}$ watts, although it would be quite easy to do so. What enables the tantalum lamp to have about twice the efficiency of the carbon filament lamp?

125. Show that it is impossible to make a carbon filament incandescent electric lamp as efficient as an arc lamp.

INDEX

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